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Mattering More-than-human Care in Biodesign

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Try to hold it, then you will lose it.

Tao Te Ching

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Preface: An Ongoing Positionality

This work is for those who seek to craft alongside the living, to weave designs with organisms as threads in the web of life, and to follow paths shaped by care and kinship, where every choice is a gesture of gentle tending.

In this dissertation, I refer to these living organisms, our companion species, as other-than-human. This term deliberately shifts away from nonhuman to resist the binary that positions humanity in opposition to all else, embracing instead a language that acknowledges interconnectedness and relationality.

As a design researcher, I have always been fascinated by how matters engage with, shape and transform socio-ecological systems in everyday life. Since 2018, I've had the opportunity to work with a wonderful group of materials that transformed my understanding of materials as a designer: materials that grow. My journey began with exploring edible tableware experiences with edible fungal mycelium from *Rhizopus oryzae*, a fungus central to the making of Indonesian tempeh in Java, Indonedia, since 1600s. This encounter unveiled the transformative potential of living organisms in crafting artefacts that shape human experiences and perceptions of the world. It also illuminated how designing and making with living organisms is an ancient, historical, and indigenous practice that stretches back through time immemorial—akin to baking bread with yeast accidentally discovered in ancient Egypt between 1300 and 1500 BCE or constructing resilient living root bridges by the Khasi tribe of India. These enduring practices and the shared care and knowledge they embody form an unsung poetry of the history of multispecies interconnectedness and interdependence.

In 2019, as part of my graduation project, I joined artist Diana Scherer's ongoing project Interwoven, where I had the opportunity to weave with roots, but those of a much more delicate system—oats. I investigated the intricate root system of oats and their remarkable ability to "weave" themselves into digitally fabricated beads for creating artefacts.

Through careful observation, extensive reading, and hands-on experimentation, I gained not only an in-depth understanding of designing with plant roots but also cultivated a personal, designerly bond with these living roots. I appreciated them as active agents, imbued with their own purposes and intelligence for thriving—a manifestation of the extraordinary vitality and ingenuity of life.

A pivotal moment in my positionality came after *Interwoven*. I had grown two low stools with oat roots. Typically, the process involves trimming the fresh grasses, but the vibrant green of living grasses still left on the stools were so stunningly beautiful that I chose to leave them untrimmed. However, this was only temporary—within days, the grasses wilted, their vibrant green turning into a dull yellow-brown. Feeling sad, I let them dry slowly in the materials lab, while thinking about what to do. Some time later, I passed by the stools and to my surprise, I noticed mushrooms sprouting from the seemingly barren artefact. At that moment, I realized that life had continued, even though the grasses had withered. This unexpected event marked a turning point in my approach, urging me to engage differently with living materials—entities that continue to grow, evolve, and transform in relationship with humans and the environment we share. I started my PhD research to dive deeper in this relationship.

In 2020, the concept of *Living Artefacts* was introduced by my supervisors at that time, Elvin Karana, Bahar Barati and Elisa Giaccardi. They invite biodesigners to expand their focus from working with "once-living materials" to engaging in an active dialogue with livingness throughout the lifecycle of artefacts. They drew attention to the socio-ecological relationships between humans and living artefacts, introducing notions such as "mutualistic care", i.e., a reciprocal and evolving relationship between humans and living organisms involved. In a similar line, I found myself deeply informed by posthumanist thinking, feminist care ethics which share thoughts in the relationality amongst beings—how we coexist with, care for, and are interdependent with other living entities on planet earth. I was also inspired by new materialist thinking, that posits a non-binary relationality between human and other-than-human, matter and meaning, rethinking subjectivity by playing up the role of other-than-human forces within the human. My work seeks to connect more-than-human thinking with the material practice of designing with livingness in biodesign. In this dissertation, I advocate for "mattering more-than-human care" in biodesign, proposing a new relational approach that foregrounds the ethical, temporal and reciprocal dimensions of designing with living organisms. The term "mattering" underscores the dual importance of care and materiality, not only as a lens through which to offer practical design guidelines but also expand epistemic understandings.

My research has encountered multiple challenges that contributed to the ongoing shaping and reshaping of my positionality. The most significant one has been a methodological challenge: to strike a delicate balance between design and science in design research. My methodology sits at the intersection of two seemingly opposing paths: the structured methodology of the lab and the fluid approach of creative practice. Bridging these worlds was not easy and required constant back-and-forth thinking between them, seeking connections while maintaining the integrity of both. The onset of the COVID-19 pandemic intensified these challenges, impacting the early, crucial stages of the project.

Especially, access to labs for understanding microbes and to interdisciplinary knowledge at the start of my journey was considered vital. Like many others, my project had to adapt, demanding patience and resilience in ways I hadn't anticipated. However, in retrospective, these incidents prompted me to shift my initial focus to my lived experiences with microbes at home (living with) and creative making with/for them, which largely benefited my understanding of microbes and our relationships in everyday life. And thankfully, the Material Incubator lab at Centre of Applied Research for Art, Design and Technology (CARADT) at AVANS university could accommodate part of my more science-oriented research experiments towards the end of the pandemic time.

Adapting to these constraints demanded resilience and patience, shaping both the project and my own growth. Now, I can say that pursuing a PhD is not just an academic endeavor; it is a life practice. It requires openness to the unexpected, the ability to observe, adapt, and most of all, to care, for all that I encounter. Reflecting on this journey, the dissertation feels less like an end and more like the beginning of something bigger as my promotor Elisa Giaccardi once said to me. It contributes to the growing conversations in biodesign, care ethics, and more-than-human design. On a personal level, it represents my evolving and intricate relationships with the materials and practices that have shaped myself.

I hope this work inspires joy and curiosity in practicing more-than-human care, inviting readers to bring care to matter and to engage with the "matters" of care within their own practices.

Glossary

Ambivalence - Mixed or conflicting feelings encountered during the design and research process, highlighting ethical and practical tensions.

Becoming-with - A concept emphasizing co-evolution and co-creation between species, where beings shape each other's lives and existences through shared experiences (Haraway 2009).

Biodesign - A design paradigm that integrates biological systems, processes, and organisms in creative process for sustainable alternatives to industrial production, novel interaction possibilities and experiences.

Biodesign Continuum - A loop process in biodesign encompassing three continuous, intertwined and interconnected stages: understanding the habitat, embodying the habitat, and perpetuating the habitat.

Care Relations - Ethical and practical engagements between entities that prioritize attentiveness, responsibility, and responsiveness to each other's needs for maintaining, continuing and repairing life-sustaining web so that we can live in it as well as possible. Importantly, relations where care is done, is actualized, regardless of whether the relations are bound to traditional types. (Combining theories of Joan Tronto and Maria Puig de la Bellacasa)

Creative Unfolding of Care - The iterative and emergent process of fostering care relationships through experimental and adaptive practices.

Cyanobacteria - Photosynthetic bacteria that absorb carbon dioxide, produce oxygen and are essential to global ecosystems, often referred to as "blue-green algae" due to their colour manifestation and metabolic similarity to green microalgae. Some sources also call them "microalgae."

Design Experiments - Concrete design activities that shape and reshape research programs in a programmatic research-through-design process.

Designerly Way of Knowing - An approach to understanding and exploring the world through the lens of design, emphasizing creativity, iteration, and material engagement.

Feminist Care Ethics - A moral theory that centers care as a virtue in human morality, which originates from feminist scholars in 1980s to challenge traditional male-centered ethics such as justice. This dissertation takes Joan Tronto's denification of care ethics, as encompassing five essential qualities: attentiveness, responsibility, competence, responsiveness and plurality.

Habitabilities - A design principle of living artefacts, concerning the way the human body and other living and non-living entities condition the livingness of an artefact.

Intra-action - A term coined by Karen Barad to describe how entities emerge and transform through their interactions, highlighting mutual constitution rather than pre-existing separateness.

Living Aesthetics - A design principle of living artefacts, concerning the type, degree, and duration of change in a living artefact over time (e.g., immediate or gradual changes in colour, form, or function), and how humans might experience it.

Living Artefacts - A new generation of artefacts that sense, grow, reproduce, adapt, and eventually die. By maintaining organisms alive in the tangible manifestation of a biodesign process, livingness will become a prominent material quality of the design outcome.

Material Qualities - The specific properties of materials, composites and artefact that are bond to the present materials. They include technical qualities, such as hardness, density and transparency; and experiential qualities, such as warm, surprising, toy-like, or foldable.

Materiality - The tangible and intangible qualities of being materials, that shape interactions and relationships within a design context.

Mattering - The process by which beings or phenomena gain significance through their relationships, interactions, and engagements with matter within a specific context, highlighting the co-constitutive role of materiality in shaping meaning and existence (Barad, 2007).

Microbes - Microbes are organisms that are too small to be seen without using a microscope, so they include things like bacteria, archaea, and single cell eukaryotes—cells that have a nucleus, like an amoeba or a paramecium. Sometimes we call viruses microbes too. (A definition from American Museum of Natural History)

More-than-human - A concept that decenters human in world-making, extending human-centric perspectives to include and honor the agencies of other things and beings.

More-than-human Care - A practice and ethic of care that moves beyond human- centered concerns to encompass the interdependent web of all entities. Rooted in feminist theories like those of Joan Tronto (1993) and María Puig de la Bellacasa (2017), it emphasizes sustaining, maintaining, and repairing relations within more-than-human worlds in order to live together as well as possible.

Multispecies Flourishing - An aspirational state where diverse species thrive in interdependent relationships, shaping each other's existences through shared processes of becoming and care.

Mutual Well-being/Thriving - A state of thriving characterized by a reciprocal relationship between the living artefact and the human. In this state, the living entities fulfill their metabolic needs, maintain vitality and stability, creating a balanced and sustainable relationality.

Mutualistic Care - A design principle of living artefacts, a reciprocal and evolving relationship between humans and living artefacts, where humans act upon a living artefact in order for it to thrive. In return for this care, the artefact continues to provide humans with (functional) benefits, for example, by being an ambient light, an air-purifier, or an oil-free colour changing paint.

Other-than-human - An alternative, non-binary term to refer to what's conventionally meant by "nonhuman", which acknowledges the presence, agency, and intertwined relations among entities in shared ecosystems.

Performativity - Performative qualities of things that elicit performances that are carried out with and through their materiality.

Photosynthesis - The process by which organisms like plants, algae, and cyanobacteria convert light energy into chemical energy, absorbing carbon dioxide and producing oxygen as a byproduct.

Posthumanist Performativity - A concept from Karen Barad (2007) that challenges anthropocentric and binary perspectives, emphasizing the entangled co-constitution of matter and meaning in processes of world-making. It underscores the performative nature of matter and distributed agencies across human, material assemblages, and beyond.

Programmatic RtD - RtD process consisting of a dynamic interplay between formulation of research programs and design experiments.

Regenerative Ecologies - The contexts and situations characterized by a disposition towards mutualism, coevolution, and cohabitation among living entities.

Relationality - The interconnectedness and interdependence of beings, recognizing that relationships constitute the essence of existence.

Research Program - Area of exploration or overarching goal in a programmatic research-through-design process. Research programs are constantly shaped and reshaped by design experiments.

Research through Design (RtD) - A research approach in which design activities and iteration play a central and formative role in the generation of knowledge.

Shared Habitat - A physical, ecological and social space that accommodates the everyday lives of humans and living artefacts.

Temporal Dissonance - The "time lag" typically experienced by humans in noticing the gradual and subtle shifts in microbial metabolism in the context of designing with living organsms.

Temporality - The state of existing within or having some relationship with time. (A definition by Oxford Languages)

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1 Introduction

1.1. KNOWLEDGE GAP

More-than-human care has been explored cross various technological and ecological contexts [1], its specific manifestation within the field of biodesign remains under-explored. Biodesign, which harnesses living systems to create sustainable alternatives to industrial processes [2], requires nuanced concepts, frameworks, and tools to address care for these organisms.

With the bigger aim to foster more-than-human relationality [3, 4] and reciprocity [5, 6], **this dissertation explores how more-than-human care can be facilitated within and through biodesign**. It focuses on everyday cohabitation with living artefacts—designs that incorporate living organisms which continue to grow, reproduce, sense, adapt, and eventually die [7].

Living artefacts provide a rich context for examining everyday entanglements with more-than-human living entities, "raising essential questions about care, symbiosis, cohabitation, and adaptation." [7] (p.39) The framework of *living artefacts* also brings forward a design principle known as *mutualistic care*, which highlights the importance of fostering reciprocal, evolving, and mutually beneficial relationships between humans and these living systems [6, 7].

Engaging with the inherent messiness and uncertainty of biological systems [8] and everyday care [5] in the lived experiences with living artefacts, this work offers a unique approach of materiality in designing more-than-human care, and explores how materiality can support the creatively unfolding of care towards living artefacts in everyday life—one that is attuned to the temporalities and needs of both human and more-than-human entities.

1.2. RESEARCH OBJECTIVES AND QUESTIONS

The main objective of this dissertation is to explore how more-than-human care can be facilitated within and through biodesign practices. Complementing this, the dissertation also intends to explore ways of understanding and engaging with a specific other-than-human living entity thoroughly—a microbe—whilst acknowledging the limitation of the human perspective. To ground the exploration, the dissertation focuses on the care for cyanobacteria, a group of photosynthetic microorganisms with potential for carbon fixation and oxygen release. These objectives are addressed through three interrelated and accumulative research questions.

1) **How can we craft the shared habitats of humans and living artefacts for their mutual well-being?** (Chapter 3, 4, 5)

2) **How can we design with temporal dissonance to foster reciprocal relationships between humans and living artefacts?** (Chapter 4, 5)

3) **How can we foster the creative unfolding of care practices for living artefacts in everyday life?** (Chapter 5)

The dissertation explores these questions with a particular focus on the lens of **materiality** and its role within each area.

1.3. METHODOLOGY

1.3.1. LENS: MATERIALITY

The research is shaped by a lens of materiality. It focuses on materiality because of the following motivations:

First, humans and other-than-humans are materially entangled [9], intra-acting [10] and becoming together [11]. This work aligns with new materialist thinking that matter is not passive or inert but possesses an active, vibrant, and transformative role in shaping human experiences and meaning-making [10, 12]. A focus on materiality can not only opens up alternative interactive experiences [13, 14], but also actively shapes how we view and act upon the world [15].

Second, care is fundamentally material practice that has tangible consequences for maintaining the web of life [5, 16]. It is also deeply embedded in technical infrastructures, embodied experiences, and material engagements [5]. A tactile and sensory approach to care can enable an intensified form of engagement and proximity, critical to understanding and enacting caring knowledge [5].

Thirdly, materiality is under-explored in facilitating multispecies flourishing in biodesign. Designing living artefacts involves assembling materials and technologies that sustains livingness and mediates care interactions. However, everyday life is quite messy and full of tensions, especially given the dynamic nature of biological systems [5, 8]. I posit that a materiality approach deeply aligns with the dynamic and uncertain nature of this context, and can support organic, ongoing care for livingness.

Finally, my experience with novel biobased materials, material-driven design [17], and an ongoing interest in materials experience [15] has fostered a deep appreciation for tangible aspects of design and interaction [18].

This dissertation introduces a materiality lens to the discourse of more-than-human care, particularly within contexts of cohabitation and coevolution [6].Through the conceptualization and creation of living artefacts, this research emphasizes materiality as central to designs that remain open to change within dynamic, everyday reconfigurations. This approach not only provides practical methods and tools for design research on more-than-human care but also deepens the understanding of how care evolves through material engagement and interaction.

1.3.2. RESEARCH PROGRAM

I undertook a programmatic *Research through Design* (RtD) process which encompasses various research and design endeavors that shaped the direction of inquiry. RtD is a research method in which design activities play a central and formative role in the generation of knowledge [20]. Particularly, programmatic RtD centers the explicit formulation of design programs acting as a foundation and frame for carrying out series of experiments, where certain insights depend on a process of change driven by an interaction between program and experiments [19, 21–23].

Within this research program, I carried out a series of research activities that progressively shaped the inquiry, formulated, and reformulated research questions (figure 1.1). These activities included literature and practice reviews, imaginary artifacts, designing living artefacts, and exploring lived experiences with microbes, both my own and those of others.

The literature and practice review laid the groundwork for identifying emerging design directions, gaps and opportunities towards the research goal. From there, I turned to a first-person perspective, autoethnography, to study my own lived experiences as a researcher with microbes in domestic contexts as a starting point [24]. This method illuminated subjective, embodied, and situated knowledge that emerged from direct interactions with microbes in daily life [25], shedding light on unforeseen tensions and challenges in sharing habitats with these other-than-human entities. Importantly, this step also allowed me to critically reflect on my positionality within the research [26].

Throughout the research, I conducted design experiments [20], which served different purposes depending on the stage of the program. Early-stage experiments were exploratory, helping to identify and refine the research direction (Chapter 3). These experiments, often situated within my own lived experience,

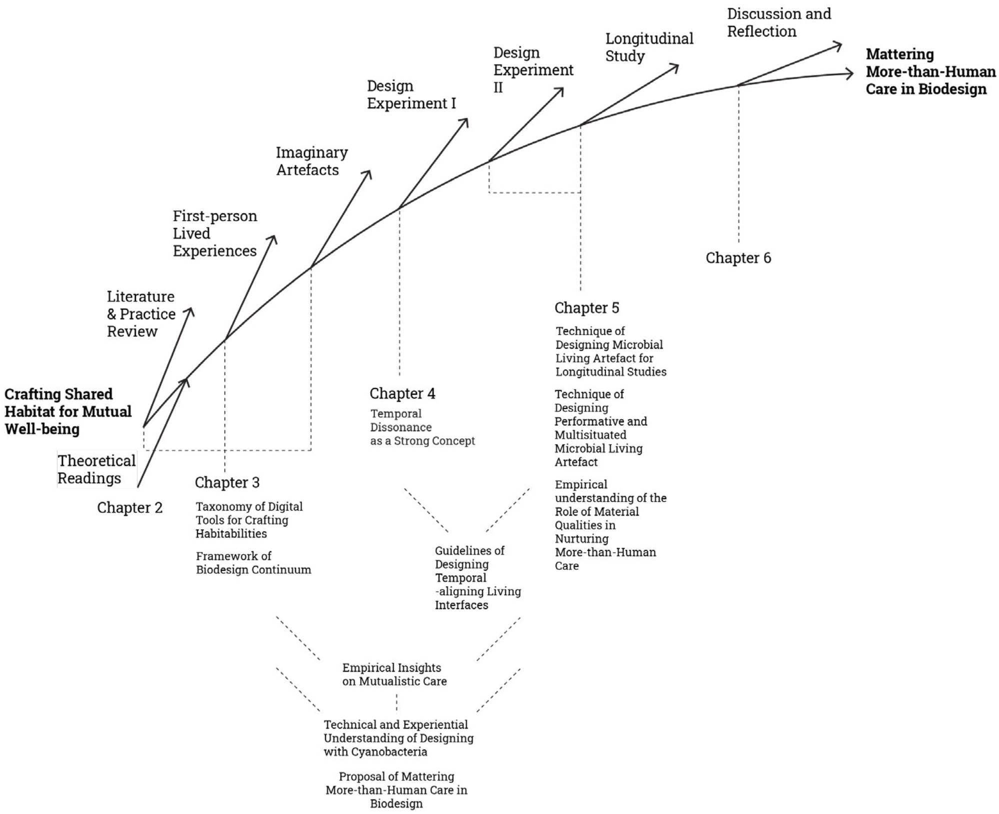


Figure 1. 1.: Diagram of the dissertation structure and contributions mapped out to a programmatic Research through Design process [19]

provided initial insights. Later experiments took on more focused aims, exploring specific design possibilities within the research program (Chapters 4 and 5). Across all experiments, I applied the material-driven design method [17], employing techniques such as material tinkering [27] and the making of performativity [28] to explore the relational and transformative qualities of materials.

Speculation played a role in several stages of the research. Haraway highlights the significance of "speculative fabulation" in crafting alternative multispecies narratives that challenge dominant human-centric perspectives [3]. In design, speculative imaginaries function as a method for envisioning alternative scenarios and fostering critical reflection [29–31]. My research employs imaginary artifacts [32] and scenarios to probe "what if" questions about the materiality of living artefacts in nurturing care practices. In the first design experiment, imaginary artefacts were also used to elicit imaginaries about reciprocal human-microbe relationships.

In the final stage, I conducted a longitudinal study [33] in my design experiment to understand the lived experiences of others. This extended engagement provided an in-depth understanding of how people interact with designed artifacts and their environments over time.

The combination of design experiments and lived experience proved invaluable, offering rich, contextual insights into how people engage with designed artifacts and their environments in their everyday lives [34]. This approach allowed me to explore the nuanced, relational, and context-specific aspects of more-than-human care for and with living artefacts.

1.3.3. RESEARCH ARTEFACTS

In Research-through-Design, research artifacts serve as catalysts and focal points for discourse within the design community ([35], p. 499). These artifacts can be tangible, like a prototype, or intangible, such as a conceptual plan [20]. Throughout my research program, various artifacts—including sketches, conceptual frameworks, and fabricated interfaces—have shaped and guided my inquiries.

Using Stapper and Giaccardi's categorization, my research artifacts have fulfilled multiple roles. Some artifacts provided direction by embedding and articulating specific research questions, while others helped to open up unanticipated design spaces. They also served as vehicles for theory building, supporting the development of new insights and frameworks within the research process. Below, I outline the impact of these artifacts.

The first set of artifacts emerged from experiments conducted during my first-person study with microbes. These transitional artifacts were crucial, bridging the gap between the literature review and the subsequent design phase. They played a significant role in refining my research focus and interests. The second set of artifacts consists of sketches and imaginary artefacts that visualize my initial ideas on how materiality could facilitate the noticing and care of microbes within living artifacts. Initially, these sketches were abstract, isolating the concepts of "noticing" and "care" into distinct apparatuses. As the sketches evolved, they began to illustrate imaginary artifacts and their scenarios of interaction. This process of sketching helped me articulate my vague ideas more clearly, making them tangible and enabling fruitful discussions and refinements of research questions with my supervisory team. Some artifacts only took shape as they were being drawn, revealing unexpected possibilities and opening up new design and research spaces.

The third set of artifacts centers around the *Cyano-chromic Interface*, which served as both an instantiation and an exploration of a design space within my research program. This interface was complemented by a series of imaginary artifacts that imagined potential interactions with the interface, helping to clarify its implications. These artifacts contributed valuable technical insights and theoretical analysis, ultimately shaping the final research question by highlighting a compelling space for in-situ studies.

Finally, the *Living Cyanobacteria Artifact* was developed, building on the findings from the *Cyano-chromic Interface*. This artifact was specifically designed for in-situ and longitudinal studies, offering an in-depth investigation within a real-life context. This artefact served as a catalyst for discussions and provided a tangible platform for exploration and reflection [20].

1.4. INTENDED AUDIENCE AND CONTRIBUTIONS

This dissertation is aimed at those who seek to design with living organisms, co-creating new realities within the web of life and guided by principles of care. It contributes to ongoing socio-ecological and ethical discussions in biodesign and relevant sub-communities of the human-computer-interaction (HCI) field, such as biological HCI, and critical and sustainable HCI, advocating for a relational approach that goes beyond functionality to embrace the interconnected, shared habitats and mutualistic care. It also contributes to more-than-human design research, extending its values to the context of biodesign, but also offering unique approach, practical methods and empirical insights on designing care for other-than-human species through materiality. Throughout, the dissertation makes the following key contributions (figure 1.1):

1.4.1. THEORETICAL AND CONCEPTUAL CONTRIBUTIONS: EXPANDING MORE-THAN-HUMAN DISCOURSE WITHIN AND THROUGH BIODESIGN

Proposal of Mattering More-than-human Care in Biodesign

This dissertation primarily contributes the proposal of "mattering more-than-human care" in biodesign, emphasizing the importance of crafting care relations through biodesign practices. It highlights materiality as a critical space for nurturing care practices, advocating for biodesign approaches that seamlessly integrate care into the materiality of living artefacts. By identifying temporality and performativity as key facets shaping care relations, it demonstrates new pathways in biodesign that center ecological and relational values, fostering an ethically grounded design practice.

Framework of Biodesign Continuum

The dissertation provides a framework of *biodesign continuum* in crafting habitabilities for biodesigners of living artefacts (Chapter 3). The biodesign continuum includes three interconnected pillars in a loop structure: *understanding the habitat, embodying the habitat and perpetuating the habitat.* It suggests an ongoing process of configuring and reconfiguring of habitats throughout the time of design and cohabitation. It emphasizes the evolving nature of living artefacts over time, and that designing living artefacts is an ongoing process.

A Concept of Temporal Dissonance

The dissertation introduces a strong concept [36] of *temporal dissonance* for biodesigners to refer to a "time lag" experienced by humans in perceiving the gradual metabolic changes in certain microbes in the context of living artefacts in biodesign. This concept enriches the space of designing with more-than-human temporalities, as it presents a crucial challenge in eliciting timely care, a generative space in which designing with temporal dissonance can lead to sensibilities of microbes, noticing and caring for them, and foster reciprocal human-microbe relationships in and through living artefacts.

1.4.2. EMPIRICAL AND EXPERIENTIAL INSIGHTS: UNDERSTANDING CARE PRACTICES AND MATERIAL RELATIONS

Understanding of the Role of Material Qualities in Nuturing More-than-human Care

The dissertation offers first insights into how material qualities of living artefacts could be meticulously designed and fine-tuned to elicit and shape novel care practices in everyday life. It illuminates the pivotal role of materiality in the care of microbial living artefacts and highlights its performative potential as an important catalyst for biodesigners seeking to develop creative care approaches specifically tailored to these living artefacts. Additionally, it uncovers important dimensions that emerge in the design of care for living artefacts.

Empirical Insights into Mutualistic Care

This dissertation contributes to biodesign by identifying challenges in caring for microbes in everyday life, with a focus on fostering mutualistic care. Through the longitudinal study, a key insight emerged from misalignments between care and functionality of the living artefact, such as the tension between optimal lighting for cyanobacteria's photosynthesis and its air purification function. The study critiques the anthropocentric focus on predefined functionality in living artefacts, proposing instead designs that support evolving mutualistic care. This shift promotes a more open-ended integration of living artefacts into everyday practices, advancing relational and ecological biodesign approaches.

Technical and Experiential Understanding of Designing with Cyanobacteria

This dissertation bridges scientific and designerly perspectives to offer both technical and experiential insights into working with cyanobacteria for biodesign. The research solidifies hypotheses on engaging with cyanobacteria's unique temporalities and surfacing their livingness through iterative tinkering and experimentation. The study also provides experiential knowledge about cyanobacteria's distinct temporal patterns and behaviors within domestic settings. The dissertation supports the design community with a holistic understanding of a cyanobacteria as a starting point for more design explorations with them, fostering a plurality of human-cyanobacteria relationships.

1.4.3. METHODOLOGICAL CONTRIBUTIONS: PRACTICAL GUIDELINES FOR MORE-THAN-HUMAN CARE IN BIODESIGN

Taxonomy of Digital Tools for Crafting Habitabilities

This dissertation introduces a taxonomy of digital tools for crafting habitabilities for living artefacts. It categorizes existing digital technologies that aid in understanding, embodying, and perpetuating the habitats of these artefacts, offering practical insights for fostering care relations between humans and living organisms.

Guidelines of Designing Temporal-aligning Living Interfaces

This includes the methods employed to design the *Cyano-chromic Interface* and the *Living Cyanobacteria Artefact*, offering practical guidelines for biodesigners to align human perception with microbial rhythms and foster reciprocal care relationships. By presenting design primitives of the interface, grounded through scientific characterization, the design space of the *Cyano-chromic Interface* offers designers starting points for living artefacts that can be situated in diverse use contexts through configurations of their components.

Technique of Designing Microbial Living Artefacts for Longitudinal Studies

This dissertation introduces a novel technique for crafting living artefacts tailored for longitudinal studies, addressing the technical and practical challenges of integrating biological systems into design research. This approach, adaptable to organisms like microalgae, bioluminescent bacteria, and flavobacteria, opens pathways for investigating various issues concerning long-term interactions in diverse contexts.

Technique of Designing Performative, Multi-situated Microbial Living Artefacts

The dissertation provides detailed descriptions of the materials and step-by-step processes involved in creating performative and multi-situated microbial living artefacts. This technique can be adapted and customized for other microbial systems, such as flavobacteria and microalgae, where changes in the artefact's form may directly influence its functionality or the well-being of the organisms. These insights offer a flexible foundation for designing microbial artefacts with diverse applications and ecological considerations.

1.5. DISSERTATION OVERVIEW

The dissertation has been disseminated through three published papers, which become part of Chapter 3, and form Chapters 4, and 5, respectively. Additionally, interspersed between chapters are visual essays exhibiting moments of lived experiences with cyanobacteria of myself and others.

Chapter 2 The Art of Living Together as Well as Possible provides the theoretical foundation for my research, situating it within broader scholarly discussions in science and technology studies (STS) and design studies. It consists of five sections that frame my practice, inform my methodology, and shape the direction of my research program. The theoretical framework draws primarily on posthumanism, feminist ethics of care, and new materialism. The first section establishes my theoretical stance, grounded in posthumanist relationality, which challenges binary distinctions between "human" and "nonhuman", "nature" and "culture". Here, it emphasizes the importance of carefully engaging with other-than-human species and fostering multispecies flourishing. The second section explores feminist ethics of care as the guiding framework for my research, focusing on the temporalities of care and its embeddedness in everyday practices. Third section introduces the context of my research—biodesign—and outline the current scholarly discourse on care within this domain. It highlights the existing gaps and propose my unique approach of "mattering," which centers on materiality and, more specifically, performativity as a critical lens. The fourth section delves deeper into performativity and care as materially entangled practices, emphasizing my focus on "how to care" as a situated and context-sensitive inquiry. Finally, the chapter concludes by presenting my organism-specific approach to care. Here, it introduces cyanobacteria as the central living organism in my research, emphasizing how I engage with this microbe through both scientific and designerly perspectives to co-develop new ways of living and caring.

Chapter 3 Crafting Relations in the Shared Habitat explores the significance of the careful consideration of how the shared habitat between humans and living organisms is biologically, ecologically and socially (re)configured in designing living artefacts. Through a comprehensive review of scholarly initiatives in designing with living organisms, the chapter provides a lens of relationality and highlight its importance in crafting habitabilities in biodesign. Then, it investigates tools designers can deploy and processes in crafting the habitat of living artefacts from a relational perspective. This process shapes my focus on crafting care relations with microbes through direct material engagement. Next, it presents my first-person experience of living with two microbes for several months. During this time, I observed and took care of the microbes, and tinkered with materials at hand to create deeper understanding and bond with them. The chapter reflects on this process, and discusses the unique tensions that arise, highlighting the need to notice and attune to more-than-human temporalities in care relations, and attention to materiality in care engagement. Finally, the chapter concludes by envisioning how materiality could foster reciprocal and socially-attuned care relations with microbes in and through living artefacts.

Chapter 4 Design Experiment I Designing with Human-microbe Temporal Dissonance presents the first design experiment. The chapter focuses on how dynamic materials can be utilized to help humans notice microbes, temporal patterns, and examines the design implications of this approach. A key concept introduced in this chapter is *temporal dissonance*, which refers to the "time lag" typically experienced by humans in noticing the gradual and subtle shifts in microbial metabolism in the context of living artefacts in biodesign. This temporal dissonance can disrupt the fluency of interactions and may hinder the timely detection and care of microbes in living artefacts, but also a generative space for alternative human-microbe relationships in and through living artefacts. The chapter introduces the *Cyano-chromic Interface*, which surfaces the photosynthetic activity of cyanobacteria (*Synechocystis* sp. PCC6803) using an electrochromic (EC) material that displays changes through a monochromatic interface. The chapter presents the temporal characterization of the interface and design space, followed by imaginary artefacts that demonstrate how the interface can be tailored for diverse functional and experiential outcomes in living artefacts. The chapter concludes by discussing the potential of designing with human-microbe temporalities to foster reciprocal relationships with microbes in and through living artefacts.

Chapter 5 Design Experiment II Caring for Microbes in the Everyday delves into the second design experiment and a longitudinal study that explores the role of materiality in facilitating creative unfolding of care practices. The chapter presents a cyanobacterial living artefact with air-purifying capabilities, and a longitudinal study where eight participants were invited to live with and care for it over a two-week period. The artefact's versatility, enabled by its color-changing, pliable, adhesive, and suspendable properties, allowed participants to place it in various locations within their domestic spaces, based on their assessment of where air purification was needed and where lighting conditions would support the artefact's vitality. The findings reveal distinct roles of materiality in nurturing care practices, particularly in relation to care labor, knowledge, and exploration. Additionally, the study highlights the complex design space that involves considerations of openness, temporalities, and semantic fitness, which needs careful navigation in order to foster organism- and context-specific more-than-human care in everyday life.

Chapter 6 Discussion and Reflection synthesizes the implications of my research contributions for biodesigners and the broader design and HCI communities engaged in designing care with and for living organisms. It begins by revisiting the research questions, offering a comprehensive summary of how they interrelate and have been addressed across the chapters of the dissertation. The chapter then outlines and expanded discussion of my contributions, categorized into three key facets: Theoretical and Conceptual Contributions, Empirical and Experiential Insights and Methodological Contributions. Following this, I critically reflect on my research methodology, particularly the integration of research-through-design, material-driven design, and the balance between theory and practice. These reflections highlight the iterative, intuitive, and hands-on nature of my approach while addressing its alignment with the interdisciplinary and relational goals of biodesign. Finally, I discuss the practical, epistemological and ethical ambivalences encountered throughout the research process, and explore ways of navigating these ambivalences. In the end, I discuss the limiations of this reserach and suggest future work.

REFERENCES

[1] K. Helms. "Designing with care: Self-centered research for interaction design otherwise". PhD thesis. KTH Royal Institute of Technology, 2023.

[2] A. D. Ginsberg and N. Chieza. "Other Biological Futures". In: *Journal of Design and Science* (2018).

[3] D. J. HARAWAY. "Making Kin: Anthropocene, Capitalocene, Plantationocene, Chthulucene". In: *Staying with the Trouble: Making Kin in the Chthulucene*. Duke University Press, 2016, pp. 99–103. ISBN: 9780822362142. URL: http://www.jstor.org/stable/j.ctv11cw25q.9 (visited on 09/03/2024).

[4] R. Braidotti. "Posthuman humanities". In: *European Educational Research Journal* 12.1 (2013), pp. 1–19.

[5] M. P. de la Bellacasa. *Matters of Care: Speculative Ethics in More than Human Worlds*. Minneapolis: University of Minnesota Press, 2017. ISBN: 9781517900656. URL: http://www.jstor.org/stable/10.5749/j. ctt1mmfspt (visited on 05/17/2023).

[6] E. Karana, H. McQuillan, V. Rognoli, and E. Giaccardi. "Living artefacts for regenerative ecologies". In: *Research Directions: Biotechnology Design* 1 (2023), e16. DOI: 10.1017/btd.2023.10.

[7] E. Karana, B. Barati, and E. Giaccardi. "Living Artefacts: Conceptualizing Livingness as a Material Quality in Everyday Artefacts." In: *International Journal of Design* 14.3 (2020), pp. 37–53. URL: http://www.ijdesign.org/ index.php/IJDesign/article/view/3957/923.

[8] A. Zeyer. "Coping with Structural Uncertainty in Complex Living Systems". In: *Science | Environment | Health: Towards a Science Pedagogy of Complex Living Systems*. Ed. by A. Zeyer and R. Kyburz-Graber. Cham: Springer International Publishing, 2021, pp. 11–29. ISBN: 978-3-030-75297-2. DOI: 10.1007/978-3- 030-75297-2_2. URL: https://doi.org/10.1007/978-3-030-75297-2_2.

[9] K. Helms. "Entangled Reflections on Designing with Leaky Breastfeeding Bodies". In: *Proceedings of the 2021 ACM Designing Interactive Systems Conference*. DIS '21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 1998–2012. ISBN: 9781450384766. DOI: 10.1145/3461778.3462048. URL: https://doi.org/10.1145/3461778.3462048.

[10] K. Barad. "Posthumanist performativity: Toward an understanding of how matter comes to matter". In: *Signs: Journal of women in culture and society* 28.3 (2003), pp. 801–831.

[11] D. J. Haraway. *When species meet*. Vol. 3. University of Minnesota Press, 2008.

[12] J. BENNETT. *Vibrant Matter: A Political Ecology of Things*. Duke University Press, 2010. ISBN: 9780822346197. URL: http://www.jstor.org/stable/j. ctv111jh6w (visited on 09/03/2024).

[13] H. Ishii and B. Ullmer. "Tangible bits: towards seamless interfaces between peo-

ple, bits and atoms". In: *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*. 1997, pp. 234–241.

[14] M. Wiberg, H. Ishii, P. Dourish, A. Vallgårda, T. Kerridge, P. Sundström, D. Rosner, and M. Rolston. "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.

[15] E. Giaccardi and E. Karana. "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.

[16] J. C. Tronto. *Moral Boundaries: A Political Argument for an Ethic of Care*. New York, NY: Routledge, 1993.

[17] E. Karana, B. Barati, V. Rognoli, A. Zeeuw Van Der Laan, et al. "Material driven design (MDD): A method to design for material experiences". In: *International Journal of Design* 9.2 (2015), pp. 35–54.

[18] E. Hornecker and J. Buur. "Getting a grip on tangible interaction: a framework on physical space and social interaction". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '06. Montréal, Québec, Canada: Association for Computing Machinery, 2006, pp. 437–446. ISBN: 1595933727. DOI: 10.1145/1124772.1124838. URL: https://doi.org/10.1145/1124772.1124838.

[19] J. Redstrom. *Making design theory*. MIT Press, 2017.

[20] P. J. Stappers and E. Giaccardi. "Research through design". In: *The encyclopedia of human-computer interaction*. The Interaction Design Foundation, 2017, pp. 1–94.

[21] T. Binder and J. Redström. "Exemplary design research". In: *Wonderground - DRS International Conference 2006,* 1-4 November, Lisbon, Portugal. 2006.

[22] L. Hallnäs and J. Redström. *Interaction design: Foundations, Experiments*. Textile Research Centre, Swedish School of Textiles, Unversity College of Borås and Interactive Institute, 2006.

[23] J. Redström. "Some notes on programme-experiment dialectics". In: *Nordes* 4 (2011).

[24] C. Ellis. "Autoethnography, personal narrative, reflexivity: Researcher as subject". In: *Handbook of qualitative research (2nd ed.)/Sage* (2000).

[25] E. Matthews. "Maurice Merleau-Ponty: Phenomenology of perception". In: *Central Works of Philosophy v4*. Routledge, 2015, pp. 177–194.

[26] A. Desjardins, O. Tomico, A. Lucero, M. E. Cecchinato, and C. Neustaedter. *Introduction to the special issue on first-person methods in HCI*. 2021.

[27] S. Parisi, V. Rognoli, and M. Sonneveld. "Material Tinkering. An inspirational ap-

proach for experiential learning and envisioning in product design education". In: *The Design Journal* 20.sup1 (2017), S1167–S1184. DOI: 10.1080/14606925.2017.1353059. URL: https://doi.org/10.1080/14606925.2017.1353059.

[28] B. Barati, E. Giaccardi, and E. Karana. "The Making of Performativity in Designing [with] Smart Material Composites". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp.1–11. ISBN: 9781450356206. DOI: 10.1145/3173574.3173579. URL: https://doi.org/10.1145/3173574.3173579.

[29] A. Dunne and F. Raby. *Speculative Everything: Design, Fiction, and Social Dreaming*. MIT press, 2024.

[30] M. L. J. Søndergaard, N. Campo Woytuk, N. Howell, V. Tsaknaki, K. Helms, T. Jenkins, and P. Sanches. "Fabulation as an approach for design futuring". In: *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. 2023, pp. 1693–1709.

[31] D. Wilde, M. Dolejsova, S. van Gaalen, F. A. Bertran, H. Davis, and P. G. Raven. "Troubling the impact of food future imaginaries". In: *Nordic Design Research Conference*. Design School Kolding. 2021, pp. 115–124.

[32] M. Blythe. "Research through design fiction: narrative in real and imaginary abstracts". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '14. Toronto, Ontario, Canada: Association for Computing Machinery, 2014, pp. 703–712. ISBN: 9781450324731. DOI: 10.1145/2556288.2557098. URL: https://doi.org/10.1145/2556288.2557098.

[33] E. J. Caruana, M. Roman, J. Hernández-Sánchez, and P. Solli. "Longitudinal studies". In: *Journal of thoracic disease* 7.11 (2015), E537.

[34] I. Koskinen, J. Zimmerman, T. Binder, J. Redstrom, and S. Wensveen. "Design research through practice: From the lab, field, and showroom". In: *IEEE Transactions on Professional Communication* 56.3 (2013), pp. 262–263.

[35] J. Zimmerman, J. Forlizzi, and S. Evenson. "Research through design as a method for interaction design research in HCI". In: *Proceedings of the SIGCHI conference on Human factors in computing systems*. 2007, pp. 493–502.

[36] K. Höök and J. Löwgren. "Strong concepts: Intermediate-level knowedge in interaction design research". In: *ACM Trans. Comput.-Hum. Interact*. 19.3 (Oct. 2012). ISSN: 1073-0516. DOI: 10.1145/2362364.2362371. URL: https://doi.org/10.1145/2362364.2362371.

2 The Art of Living Together as Well as Possible

"If I have a dog, my dog has a human;
what that means concretely is at stake."

—Donna Haraway

This chapter provides the theoretical foundation for my research, situating it within broader scholarly discussions in science and technology studies (STS) and design. It consists of five sections that frame my practice, inform my methodology, and shape the direction of my research program. The theoretical framework draws primarily on posthumanism, feminist ethics of care, and new materialism.

The first section establishes my theoretical stance, grounded in posthumanist relationality, which challenges binary distinctions between "human" and "nonhuman", "nature" and "culture". Here, I emphasize the importance of carefully engaging with other-than-human species and fostering multispecies flourishing. The second section explores feminist ethics of care as the guiding framework for my research, focusing on the temporalities of care and its embeddedness in everyday practices.

In the third section, I introduce the context of my research—biodesign—and outline the current scholarly discourse on care within this domain. I highlight the existing gaps and propose my unique approach of "mattering," which centers on materiality and, more specifically, performativity as a critical lens. The fourth section delves deeper into performativity and care as materially entangled practices, emphasizing my focus on "how to care" as a situated and context-sensitive inquiry.

Finally, the chapter concludes by presenting my organism-specific approach to care. Here, I introduce cyanobacteria as the central living organism in my research, emphasizing how I engage with this microbe through both scientific and designerly perspectives to co-develop new ways of living and caring.

2.1. POSTHUMAN RELATIONALITY IN DESIGN RESEARCH

The Anthropocene—a geological epoch marked by profound human influence on Earth's systems—has been shaped by industrialization, technological advancement, and capitalist practices that prioritize extraction and exploitation over ecological balance [1–3]. Addressing this crisis requires moving beyond quick technological fixes [4] and embracing a deeper relational shift that challenges the disconnection between humans and other species. This necessitates rethinking the ways design can support a collective reimagining of more inclusive and sustainable futures.

Design research turned to posthumanism to move beyond anthropocentric, human-centered frameworks which is "insufficient to think and make in the face of the challenges of the Anthropocene and digital society" [5]. A posthumanist view in design challenges the dominant binary of "human" versus "nonhuman" and instead acknowledges the complex entanglements, agencies, and interdependencies that shape the world [6, 7].

This perspective has catalyzed a growing body of research, prompting the development of new frameworks, methods, and practices that decenter the human and integrate other-than-human perspectives [7, 8], including both ecological [9, 10] and technological systems [11, 12]. These contributions formed a distinctive area of research termed "more-than-human design," which underscores the necessity of a human-decentered approach to design that aligns with the ethical and ecological imperatives of the Anthropocene. In the sections below, I unpack two theoretical learnings from posthuman relationality in my design research, "carefully relating to other-than-human beings," and "multispecies flourishing."

2.1.1. CAREFULLY RELATING TO OTHER-THAN-HUMAN BEINGS

In *Companion Species Manifesto*, Donna Haraway introduces a relational ontology in which "beings do not pre-exist their relatings" [13]. Reflecting on human-dog companionship, Haraway states that dogs are about the inescapable, contradictory story of relationships, which are the co-constitutive relationships. Expanding this idea in *When Species Meet*, Haraway introduces the concept of "becoming-with", elaborating that "if we appreciate the foolishness of human exceptionalism, then we know that becoming is always becoming with—in a contact zone where the outcome, where who is in the world, is at stake." [14] (p.244)

Haraway's ideas resonate with Karen Barad's concept of "intra-action," which posits that entities and boundaries emerge through dynamic relational processes rather than pre-existing independently [15]. In Haraway's ontological exploration of human-animal relationality in laboratory contexts, she applies this lens, suggesting that animals in labs are response-able to humans just as humans are to them. She describes this as a mutual relationship where "people and animals in labs are both subjects and objects to each other in ongoing intra-action." [14] (p.71) And yet, such response-ability does not build upon "symmetrical shapes and textures for all parties." (p.71)

This is an interesting view and also bears ethical implications. She argues that although using a model organism in an experiment is a common necessity in research, such necessity and the justifications do not obviate the obligations of care and sharing pain, and that "acquiring knowledge is never innocent." She comments on instrumental relations between humans and lab animals:

> "I am arguing that instrumental relations of people and animals are not themselves the root of turning animals (or people) into dead things, into machines whose reactions are of interest but who have no presence, no face, that demands recognition, caring, and shared pain. Instrumental intra-action itself is not the enemy; indeed, I will argue below that work, use, and instrumentality are intrinsic to bodily webbed mortal earthly being and becoming. Unidirectional relations of use, ruled by practices of calculation and self-sure of hierarchy, are quite another matter (P.71)."

Haraway insists that care must be central to these relationships. In *When Species Meet*, she explores the ethical complexities of working with other species in instrumental contexts, such as laboratories. She advocates for empathy, care, and accountability as essential elements of ethical research practices involving other-than-human species [14]. She calls to "stay with the trouble" to confront these complexities, committing to meaningful and ethical engagements with other species [4].

Building on these ideas, Maria Puig de la Bellacasa in *Matters of Care* further unpacks the interplay between care and relationality. She argues that "relations of thinking and knowing require care and affect how we care. Not only do relations involve care; care is relational per se" [16] (p.69). For Puig de la Bellacasa, livable relating necessitates particular care, especially in asymmetrical relationships where one being is more dependent on the other for survival (cf. [14]). She writes, "care appears as a doing necessary for significant relating at the heart of the asymmetrical relationalities that traverse naturecultures and as an obligation created by 'necessary joint futures'" (p.83). Care, she argues, facilitates relationality that makes each other significant, enabling humans and other-than-humans to "co-train each other to live, work, and play together." (p.83)

My research engages deeply with the significance of care in multispecies relationality. Care is not only essential for such relationships; it also reshapes reality by generating new possibilities for relating-to and living-with others [16]. Haraway's insights into human-animal relations in laboratory settings are particularly relevant. In biodesign practices that involve lab practices, designers and researchers form mutually response-able relationships with "lab organisms." **Aligning with Haraway's point of view, this research recognizes the instrumental aspects of these relationships, yet the necessity of scientific research for a greater good, we must reciprocate with empathy, care, and responsibility, ensuring that these interactions are grounded in ethical and meaningful engagement.**

2.1.2. MULTISPECIES FLOURISHING

Originating in ecological sciences, the term "multispecies" refers to interactions between various species within shared ecosystems [17]. Anthropology later adopted this perspective through multispecies ethnography, which highlights the interconnected lives of humans and other-than-humans shaped by political, economic, and cultural forces [18]. The relationality approach to understanding multispecies emphasizes "becomings," or the emergent relations formed through nonhierarchical alliances and symbiotic interactions (cf. [19]).

In response to the ongoing mass extinctions and ecological crises driven by human activity, it is important to reinvent the conditions necessary for multispecies flourishing, such as "kin-making"—forming meaningful relationships with other species—as a critical step toward fostering flourishing ecosystems [4] (p.145). Anthropologist Anna Tsing explores ways for making this happen. In *The Mushroom at the End of the World*, she introduces the concept of *arts of noticing*. Tsing explores the precarity and interconnections of multispecies landscapes, particularly in environments marked by environmental degradation and capitalist exploitation. Through her study of matsutake mushrooms thriving in ruined landscapes, she reframes these spaces as sites of resilience, collaboration, and multispecies survival rather than decline [2]. Tsing's work encourages designers to notice and engage with the less visible dynamics of more-than-human coexistence, such as unintended collaborations and emergent systems of care, providing a foundation for design practices aimed at multispecies flourishing.

Designers across fields and communities such as biodesign and biological, ecological, sustainable and critical human-computer interaction (HCI) have begun to explore practices that foster relational ecologies and multispecies flourishing with certain living organisms within certain ecologies created through these practices. These include methods such as noticing [20, 21], caring [22–25], and cohabitation [9]. For instance, Liu et al. [20] build on Tsing's concept of *arts of noticing* by designing tools to aid mushroom foragers in noticing and connecting with fungi. These tools promote engagement, attunement, and expansion of human relationships with more-than-human entities.

Amongst all, rather than supporting flourishing together with other species in their naturally evolved habitats, biodesign practices feature a deliberate move to appropriate certain selected living organisms in what is considered to be "human environment," and explore new ways of flourishing together within new ecologies. By integrating organisms such as bacteria, fungi, and algae into everyday artefacts, biodesign paradigm challenges existing industrial production modes while exploring more sustainable and regenerative futures [26, 27]. Projects such as *Living Things*, which incorporates microalgae cultivation into domestic furniture, demonstrate a possibility of human and microalgae cohabiting in shared spaces [28]. These artefacts explore new types of "symbiosis and cohabitation while raising critical questions about care, responsibility, and adaptation in everyday contexts." [27] (p.39) Such living artefacts, either practical or speculative, ongoingly extend our proximity to other living beings in diverse environments, including domestic settings [29], public spaces [30], and the human body [31, 32].

Whilst some early research considers biodesign as a production paradigm for the 21st century [33], others also critically discuss the possible pitfall of biodesign being merely a drop-in replacement in the current unsustainable economic system, or promoting only the well-being of humans and a few selected monospecies [34]. Recent advancements in biodesign increasingly emphasize ecological and ethical dimensions, focusing on relationality and responsibility. For example, Chen et al. [35] introduces the concept of *microbial revolt* to acknowledge microbial agency in design processes, while Kim et al. [36] explores methods of *becoming microbes* to foster empathy and sensibilities toward microbial life. Other researchers expand biodesign's multispecies scope, such as Bell et al.'s exploration of multispecies-driven degradation of 3D-printed biomaterials [37] and Groutars et al.'s ecologically oriented design approach that situates living artefacts within intricate webs of life [38]. The framework of *regenerative ecologies* further highlights how living artefacts can catalyze cohabitation and coevolution between humans and other-than-human species [39].

My research aligns with the above critical approaches towards designing with living organisms, particularly looking into nuances of socio-ecological considerations within the new ecologies emerged through situating living artefacts in everyday lives. I am informed by the concept of noticing, engaging with the subtle and often invisible differences of other-than-human species [2] . I situate this practice within the multispecies context of biodesign, viewing it as a site for resilience and collaborative survival [2] between human and the specific species involved. Specifically, I focus on living artefacts and the ecological and ethical complexities they embody [4], working toward fostering regenerative ecologies [39]. By foregrounding care as a relational and ethical commitment [4, 16], my work seeks to explore how designers can cultivate more-than-human care within and through biodesign practices. This approach aims to contribute creative ways of how design can support this particular context of "multispecies flourishing" [4] while navigating the intricate challenges of designing with living systems in an interconnected world.

2.2. FEMINIST ETHICS OF CARE IN MORE-THAN-HUMAN WORLDS

Feminist and posthumanist theories often intersect in their critique of dominant structures and their emphasis on relationality. The concept of care, central to feminist ethics, is highly relevant in more-than-human contexts. Ecofeminism—a diverse field that examines the intersections of ecological and feminist concerns—critiques the systemic oppression of both women and the environment under patriarchal capitalism. Feminist scholars argue that the exploitation of women and nature is interconnected, both being marginalized and commodified as resources within socio-economic structures shaped by historical, social, and economic contexts [40–43]. Val Plumwood critiques the "logic of dualism" in Western thought, which she argues perpetuates both ecological and gender domination [43]. Ecofeminism promotes an ethic of care that values empathy, responsibility, and relationality, challenging exploitative models of resource use in favor of practices grounded in mutual care and respect [16, 42].

Political theorist Joan Tronto's influential definition of care—"everything we do to maintain, continue, and repair 'our world' so that we can live in it as well as possible"—situates care as a moral and political practice [44]. Tronto emphasizes the ethical dimensions of care, identifying four phases: *Caring about, noticing* *the need for care; Taking care of, Assuming responsibility for meeting that need; Care-giving: Performing the tasks required to provide care; Care-receiving: Understanding the response of the cared-for to the care provided.* These phases are underpinned by four ethical qualities: *attentiveness*, *responsibility*, *competence*, and *responsiveness*. Tronto's framework has profoundly influenced care ethics by highlighting the relational, embodied, and political dimensions of care.

In more-than-human worlds, care becomes a critical ethical and ecological practice, especially given that "not all humans or others or objects in the world are equally able, at all times, to take care of themselves" [44]. Increasing attention has been paid to care for other-than-human species as a political and ecological concept, particularly within feminist and posthumanist techno-science [18, 45–47].

Donna Haraway, in *Staying with the Trouble*, introduces the concept of "making kin"—a call to form connections that transcend traditional boundaries of family, species, and hierarchy [4]. Haraway's slogan "Make kin, not babies" (p.102) provocatively advocates for new forms of multispecies kinship that prioritize sustainability and collective flourishing. This vision calls for an ethic of care that is inclusive of all beings, human and other-than-human alike, grounded in solidarity and mutual responsibility.

Maria Puig de la Bellacasa, in *Matters of Care*, broadens the discourse of care ethics to encompass more-than-human relationships [16]. She conceptualizes care through three interwoven dimensions: *Labor/Work: The material and practical actions of caregiving. Affect/Affections: The emotional dimensions of care, including empathy and attachment. Ethics/Politics: The broader moral and social frameworks that shape care practices.* Bellacasa positions care as a decentered, relational ethic that recognizes the interdependence of all beings. She advocates for speculative thinking to imagine and sustain care relationships in more-than-human worlds, emphasizing care as a practice of "living as well as possible" within a complex web of life (p.219).

2.2.1. TEMPORALITIES OF CARE

In *Matters of Care*, Maria Puig de la Bellacasa introduces the concept of *temporalities of care*, emphasizing that care inherently requires time—a kind of unexceptional, dedicated time often undervalued in modern productivity paradigms. This "care time" involves creating space to align with the diverse temporal rhythms of those being cared for, whether children, the elderly, or cells in a petri-dish [16]. Using soil ecology as an example, Puig de la Bellacasa describes soil as a multispecies world with temporalities that demand an intensification of attention and involvement. She writes, "From a temporal perspective, these obligations require an intensification of involvement in making time for soil-specific temporalities." [16] (p.172) Here, "care time" emerges as the act of "making time" to engage with the complex, intertwined timelines of more-than-human agencies (p.171).

Permaculture, a practice and movement dedicated to designing sustainable human habitats by observing and aligning with nature's patterns, also reflects this principle. Permaculture emphasizes "thoughtful and protracted observation" before taking action on the land and its processes [48]. This immersive practice necessitates synchronizing with ecological cycles, effectively cultivating care time by respecting the temporal rhythms of soil and other natural systems [49].

Three temporalities intersect in care work: "care time", the accelerated and future-oriented "productionist time" of technoscientific innovation, and the slower, cyclical "biological time" rooted in living systems. Ecofeminist philosopher Mary Mellor articulates biological time as the cycles of the human body and the daily needs of health and sustenance—such as sleep, food, and shelter—juxtaposing it with the linear, outcome-driven logic of productionist time [50]. Care time often conflicts with productionist time, as the attention to ecological cycles, like soil life, disrupts the linear pace of agricultural or industrial productivity. Ecological relations demand consideration of multiple, interconnected timescales, resisting a single, homogenized temporal framework [51].

Puig de la Bellacasa, however, warns against interpreting care time as an effort to recover a sense of oneness. Instead, she advocates for recognizing the real difficulties and complexities of fostering multifaceted, caring relations among humans, other-than-humans, and the systems in which they coexist. This requires fine-tuning our attentiveness to the rhythms of the "other" and the specific relational dynamics at play, rather than attempting to homogenize various temporalities into a universal cadence [16, 52].

Building on these insights, my research foregrounds two key perspectives:

1. **Care absorbs and disrupts time**: Caring requires a conscious effort to "make time" and resist the accelerated pace of productionist temporalities. This disruption is necessary to nurture relationships and attentiveness to other-than-human entities.

2. **Care requires attuning to other time**: Caring for other-than-human species in biodesign involves navigating diverse temporalities—those of living organisms

and of humans. This interplay challenges designers to respect and align with these rhythms rather than impose human-centric timelines.

This dissertation takes the time to explore the temporalities of care, investigating how design can create opportunities to cultivate care time. By offering tools and frameworks, design can help attune human practices to the temporal rhythms of other-than-human entities, fostering alternative, reciprocal relationships.

2.2.2. UNSETTLING CARE IN MUNDANE EVERYDAYNESS

Feminist ethics of care focuses deeply on the politics of everyday life, addressing the ordinary and mundane practices that shape how we live [53]. While care often carries positive connotations, both Haraway and Puig de la Bellacasa highlight its inherent messiness and discomfort, particularly in the context of everydayness. Contemporary engagements with care not only emphasize its importance but also caution against an overly optimistic view of its practice, urging us to continuously "unsettle" care [16, 54]. As Haraway reflects in *When Species Meet*: "We learn to be worldly from grappling with, rather than generalizing from, the ordinary. I am a creature of the mud, not the sky" [4] (p.3). Care in more-than-human relations is often entangled with moral ambiguities, emotional complexities, and the discomfort of navigating the unfamiliar [54].

Engaging with these complexities requires attentiveness and a practical, material engagement with the unsettling and unfamiliar. People become "obliged" to care not through abstract moral principles but in the material, messy realities of relational arrangements [16]. This obligation is cultivated through hands-on practices, curiosity, and a responsive love for the needs of the "other" [16]. Ethicality in care emerges in the muddled, concrete situations where the necessity of care is deeply felt (p.166). Feminist scholar Annemarie Mol similarly argues that care work is characterized by unexpectedness and indeterminacy, requiring continuous "tinkering" to address the specific relationalities at stake [55].

In design and HCI, everyday more-than-human care has been explored across various contexts. Examples include care imaginaries in home IoT systems [56], tensions in caregiving for loved ones [57], feminist approaches to tactful care in design [58], community-driven care practices in farming [59], considerations of animal welfare [60], and the principle of *mutualistic care* for conceptualizing living artefacts in biodesign [27]. These explorations align with Puig de la Bellacasa's notion of *thinking with care*, which attunes perception to the material and relational dimensions of care (p.116).

The everyday context provides a rich foundation for this dissertation, with its inherent messiness and uncertainty resonating with the dynamic nature of living systems. Building on these discussions, this research examines care in biodesign, focusing on the mundane, everyday practices of cohabiting with other-than-human entities. It investigates the tensions and challenges involved in caring for these entities, emphasizing the evolving and situated nature of care relationships. These tensions are framed within an approach that combines speculative thinking—imagining what care could be—with hands-on practices rooted in the neglected, yet essential, everydayness of care [16] (p.111). The dissertation centers on the "how" of care, grounding care ethics in the specificities of situations rather than in abstract moral dispositions.

2.3. CARE IN BIODESIGN

Biodesign inherently engages with the everyday, where care is woven into the mundane, messy, and temporally entangled interactions with biological systems. It also intersects with multiple biological timescales, reflecting the dynamic and evolving nature of living artefacts. As ambivalent as care itself, designing with living organisms inevitably entails power asymmetries—where the human designer or cohabitant may hold authority over the organism's conditions for survival. These organisms often rely on sustained environmental parameters in order to remain alive and continue "functioning" in ways beneficial to humans. In this context, I draw on Puig de la Bellacasa's conception of care as a multi-layered, non-innocent, thick, and mundane doing rather than a purely moral disposition [16]. Simultaneously, I frame care as a potential disruptor of this inherent imbalance—an opening towards more generative, co-constitutive forms of relation with living organisms that resist purely functional or instrumental logics [16].

Only in recent years has the concept of care in biodesign gained scholarly attention, with researchers beginning to explore its ethical and practical implications. This section unpacks two approaches: *mutualistic care* [27] and *microbial care ethics* [61].

2.3.1. MUTUALISTIC CARE

Early biodesign practitioners introduced care by exploring reciprocal relationships between humans and living artefacts. For example, Teresa van Dongen's *Spark of Life* (2014) [62], a lamp powered by electrogenic bacteria, requires people to nourish the bacteria periodically for the lamp to function. Van Dongen envisioned this act of feeding as fostering a closer relationship between the people and the artefact [62]. Similarly, her project *Ambio* [63], a lamp containing bioluminescent bacteria, integrates care through an act of tilting the lamp to provide oxygen, essential for both its functionality and the bacteria's well-being.

These projects inspired the concept of *mutualistic care* of the *living artefacts* framework [27], emphasizing the interdependence between humans and living organisms in biodesign. This notion encourages designers to create artefacts that facilitate reciprocal relationships, where humans care for living organisms in exchange for functional or aesthetic benefits. Expanding this idea, Karana et al. connect *mutualistic care* to broader goals of *regenerative ecologies*, posing the questions: "How do we enable creative assemblages and reciprocal practices in everyday interactions with living artefacts that foster interconnectedness, interdependencies, and mutualism? How can we foster a comprehensive understanding of (and design for) mutualistic care practices that extend beyond the human realm to encompass more-than-human entities?" [39]

Karana et al. also link *mutualistic care* to the concept of *living aesthetics*, which focuses on how humans experience the type, degree, and duration of change in a living artefact over time [27]. They argue that *living aesthetics* can facilitate *mutualistic care*, noting that "as the changes in living materials indicate the organism's well-being or struggle, the careful crafting of living aesthetics can help facilitate unique care-related actions in the long run." (p.46) This understanding aligns with Maria Puig de la Bellacasa's observations on the temporalities of care, while adding a practical dimension by connecting care actions to the temporal expressions of living organisms.

2.3.2. MICROBIAL CARE ETHICS

Microbes, as some of the most frequently explored organisms in biodesign, bring unique ethical and practical challenges to the field. Rachel Armstrong's *Biodesign for a Culture of Life* [61] focuses on these challenges within urban and built environments. By analyzing biodesign projects at larger scales, such as the built environment, Armstrong emphasizes the need to consider microbes' spatial and temporal needs to foster meaningful interactions and equitable exchanges.

One example is the *Active Living Infrastructure: Controlled Environment*

(ALICE) project, a digital platform and interface for "interspecies communication" between humans and microbes. *ALICE* visualizes microbial metabolism in real-time through artistic digital expressions, exploring ways to temporally align human and microbial interactions. Armstrong argues that such designs exemplify how biodesign can acknowledge the agency and contributions of microbes, positioning them as active participants in the design process.

Armstrong illuminates preliminary insights for an *ethic of care* in biodesign. First, she emphasizes the importance of recognizing microbes' omnipresence, agency, and their pivotal role in shaping the biosphere through "metabolic contributions in transforming the planet from a hostile to a life-supporting system." (p. 14) Second, she advocates for decentering human designers as sole authors of biodesign, instead positioning them within "an expanded community of multi-species participants" (p.14) to enable co-creation with microbes. Finally, Armstrong underscores the principle of "mutual thriving" as fundamental to establishing an ethics of care, framing biodesign as a collaborative, world-making process that facilitates symbiotic relationships between humans and microbial life. This perspective redefines design as a shared endeavor, emphasizing the need for ecological reciprocity and new forms of symbiosis.

Both *mutualistic care* and Armstrong's *microbial care ethics* highlight the importance of respecting diverse temporalities in biodesign. Caring in this context requires acknowledging the unique biological timescales of other species, making time for their care, and finding ways to bridge these temporal differences practically. This formed the theoretical pillars for my exploration of temporality in care. Besides, my research builds on the mutualistic/mutual quality of care in biodesign, focusing on the mutual "well-being" or "thriving" of both the human and the living organism.

While calls to incorporate care into biodesign are gaining attention in design research, the link between conceptual, methodological and practical strategies for fostering more-than-human care has not been explored comprehensively. My approach builds on posthumanist relationality, feminist care theories, and biodesign frameworks, and contributes to more-than-human care in biodesign uniquely by placing "mattering" at the center. I use "mattering" as a connective thread between the practical and the conceptual, examining it as a pathway to cultivate care. The following section outlines the theoretical foundation and motivations behind this approach.

2.4. MATTERING MORE-THAN-HUMAN CARE IN BIODESIGN

According to Karen Barad, "mattering" is an ongoing process through which the material world and its meanings are co-constituted [15]. It is within these entangled agencies and practices of matter and meaning that technoscientific worlds "come to matter" [15]. Building on this, Maria Puig de la Bellacasa emphasizes that care is not only a moral disposition but also a consequential and transformative one in the material world [16].

In this section, I propose "mattering" as a conceptual and methodological approach to more-than-human care. This approach emphasizes care as deeply embedded in material practices and materiality itself. By focusing on posthumanist performativity and the entanglement of care with material processes, **I aim to explore how care can come to matter through ongoing process of mattering**.

2.4.1. PERFORMATIVITY MATTERS

New materialist thinking challenges binary distinctions between matter and meaning, emphasizing the dynamic relationality that integrates inhuman forces into the constitution of subjectivity [64]. Key proponents of this school, such as Jane Bennett and Karen Barad, highlight the active, performative roles that matter plays in shaping the world. In *Vibrant Matter: A Political Ecology of Things*, Jane Bennett advocates for acknowledging the "thing-power" of materials, arguing that objects possess agency capable of influencing human thought, behavior, and relationships [65]. Similarly, Karen Barad's theory of "posthumanist performativity" redefines discursive practices as material (re)configurations of the world that involve human and other-than-human matter alike [66]. These perspectives position materiality not as a passive backdrop but as an active participant in co-constructing interactions, relationships, and knowledge production [15, 66].

In design, materials play a crucial role not only in delivering technical properties but also in shaping experiential and relational values. Materials have the "power" to make people sense, feel, think, and act in specific ways [67]. The transformative agency of materials is encapsulated in the *materials experience* framework [70], which explores the narratives and interactions that emerge between humans and other-than-human materials. For instance, materials can evoke subjective, emotional, interpretive, and performative responses [67].

Material-Driven Design (MDD), introduced by Karana et al. [67], builds on this understanding by emphasizing the experiential potential of materials. It challenges designers to engage with materials not only for their functional utility but also for their capacity to inspire, guide, and shape the design process and outcomes [67].

MDD inherently adopts an anti-anthropocentric stance, recognizing materials as active participants in the design process and advocating a holistic approach to navigating sustainability [68]. This perspective has been extended to biodesign, where living materials such as bioluminescent algae [69] and flavobacteria [31] introduce unique biological processes and aesthetic experiences into design. For example, bioluminescent algae emit a glowing light when agitated, presenting opportunities for designers to consider not only how these living materials perform—in terms of growth, adaptation, and interaction with their environments—but also how they prompt human actions, such as shaking the algae culture to activate its glow.

Giaccardi and Karana [70] have called for greater attention to the performative qualities of materials, emphasizing their ability to actively shape daily practices and ways of doing. Building on this, Karana et al. [71] explored how the performative aspects of materials can invite novel forms of social practice, as exemplified in their study of "tuning the radio" as a mundane activity transformed through material interaction. To support designers in leveraging material performativity, Barati et al. [72] developed a framework for designing materials that elicit specific human actions.

My perspective on materiality focuses on the performative qualities of both living and nonliving materials in eliciting care actions and practices, fostering co-constructed care relations. This approach aligns with new materialist thinking, which recognizes the relational entanglements between humans and materials and their co-creative processes. At its core, this view resists anthropocentrism, advocating for a design ethos that foregrounds the agency of materials in co-shaping care practices.

2.4.2. MATERIALLY ENTANGLED CARE

Care is inscribed in the materiality of more-than-human things [16]. Maria Puig de la Bellacasa highlights the intricate relationship between care and materiality, framing care as a practical, material action that sustains the web of life. She presents a feminist perspective that emphasizes care as embedded in the mundane, situated, and specific practices of maintenance that uphold daily life, rather than being rooted in abstract moral dispositions. People are drawn into caring through the material and relational entanglements of their practices, often shaped by the messy constraints of the material world rather than by ideals alone.

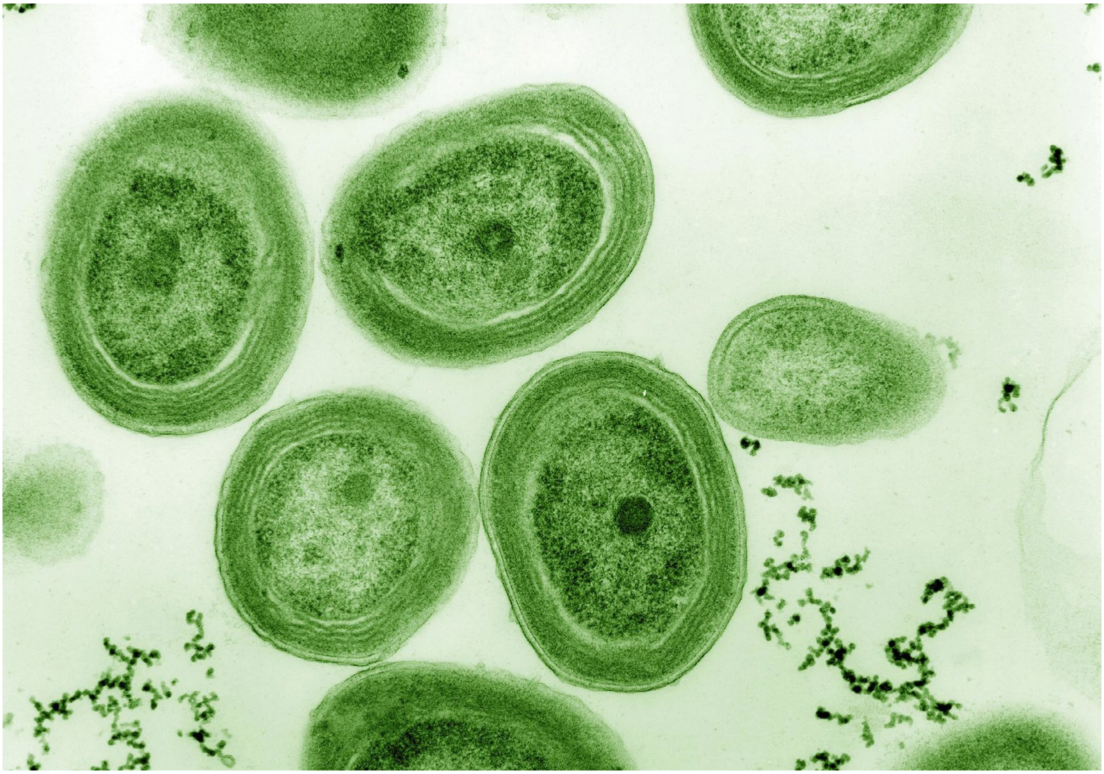
Delving into Barad's concept of "touch" [73], Bellacasa advocates for a "touching vision" in care - an approach to knowing that involves direct material engagement rather than distant observation. This tactile and sensory approach fosters a form of caring knowledge grounded in intensified engagement and proximity [16]. "Touch" in this sense is inherently reciprocal, prompting critical reflection on the mutual interactions and responsibilities shared between humans and other-than-human entities.

Building on these ideas, I propose that materiality serves as a vital lens for examining more-than-human care. In feminist design research, materiality has been explored in relation to intimate human care. For example, Helms [74] offers a nuanced understanding of everyday care practices for oneself, other humans, and other-than-humans. She examines the creation of fiddling objects designed for human babies, which are informed by the leaky, entangled materialities of breastfeeding bodies, such as human breast milk and cow's milk. Her work illustrates how the human self is materially intertwined with other-than-humans. Through her designs, Helms reflects critically on the materiality of interaction design, particularly in the context of digitalization. She underscores the expressive and shapeable qualities of materials, advocating for greater attention to nondigital processes and more-than-human agencies in design.

Despite these advancements, the materiality of care remains underexplored in the realm of biodesign. Living artefacts, with their dynamic and unpredictable biological systems, offer a compelling context for investigating materiality in everyday care practices involving more-than-human life. Current approaches to care for living artefacts are dominated by "care labels" as instructions of care, such as seen in *Biogarmentry* [75], or prescribed interactions that provide what the living organisms needs, such as seen in *Ambio* [63] and *Tardigotchi* [76]. **However, these approaches may be insufficient to address the messiness of the everyday and the entanglements of care with the material reality. Incorporating the concepts of "performativity" and care as situated, material practice, my research seeks to explore how materiality can support care for living artefacts within the complexities of everyday life. By focusing on the how of care, I ground care ethics in specific, lived situations [16], aiming to reveal new pathways for fostering more-than-human care through**

Cyanobacteria bloom in lake Erie
©NASA Earth Observatory

Cyanobacteria under microscope
©The Planetary Society



the material entanglements of biodesign.

2.5. CARING FOR CYANOBACTERIA

There exists a fascinating yet underexplored landscape in more-than-human care: the intricate and dynamic relationship between humans and microbes within both traditional and emerging ecosystems. Microbes often challenge human perception due to their microscopic scale [32], remaining largely unnoticed. However, microbial living artefacts, with their diverse forms and behaviors, offer unique opportunities for humans to notice, understand, and engage with microbes in unprecedented ways.

As some of the earliest, most abundant, and diverse life forms on Earth, microbes play a fundamental role in natural cycles that sustain life and maintain the global climate [77]. Their influence is pervasive, extending to the human body—inhabiting our skin, gut, and membranes. Microbes aid in digestion, bolster immunity, and define humans as "holobionts by birth" [78]. Beyond this biological intimacy, humans actively collaborate with microbes in ancient and indigenous practices like fermenting bread, brewing beer, and constructing bridges. In biodesign, these biological affordances are harnessed for innovative functions, from air purification to energy generation. Microbes are even being integrated into computational systems as sensors or displays, referred to as "living bits." [79]

2.5.1. AN ORGANISM-SPECIFIC APPROACH TO CARE

Whilst acknowledging that microbes encompass a vast diversity of species with immensely varied abilities and idiosyncrasies, my research centers on a specific group of microbe—cyanobacteria—to instantiate, situate and probe the underexplored landscape of microbial care in biodesign. And more specifically I engage with three different species in my research, amongst them, *Spirulina platensis* is centred in the early stage of my research and *Synechocystis* sp. PCC6803 comes later in lab exploration. This organism-specific approach resists the tendency to generalize microbes as a monolithic entity or depict them as an alien "other." Instead, it emphasizes their unique temporalities, habitat requirements and care needs. By focusing on specificity, my work reframes the role of the human designer as a modest learner attuned to microbes. To achieve a holistic understanding of cyanobacteria, largely informed by the Material-Driven Design method, I integrate both scientific inquiry and designerly exploration, bridging multiple ways of knowing to engage deeply with these remarkable organisms.

2.5.2. THE ART AND SCIENCE OF CYANOBACTERIA

Cyanobacteria, often called blue-green algae, have profoundly shaped Earth's history. Around 2.4 billion years ago, they triggered the Great Oxidation Event, transforming Earth's atmosphere and paving the way for oxygen-dependent life [80]. Today, they remain vital to the global carbon cycle, converting carbon dioxide into organic material through photosynthesis [81]. Their metabolic versatility, including nitrogen fixation, has made them a focus of research in microbiology, ecology, and biotechnology [82–84]. In design, cyanobacteria are increasingly recognized for their potential in material production, renewable energy, and carbon sequestration [85]. For instance, their ability to capture carbon and release oxygen has been explored in addressing climate change and improving air quality [86, 87].

Cyanobacteria have also inspired art and design projects. In *Unlearning Photography: Listening to Cyanobacteria*, bioartist Risk Hazekamp critiques the toxicity of analog photography by using cyanobacteria's photosynthetic processes to develop sustainable photographic techniques [88]. In this work, Hazekamp relinquishes control, instead creating conditions where cyanobacteria's biological processes generate the image [88]. Similarly, the design and architecture firm ecoLogicStudio has explored *Spirulina platensis*, a species of cyanobacteria, in projects like *BioBombola*. This initiative invites people to cultivate domestic spirulina gardens, providing both a sustainable protein source and an air-refreshing hub that absorbs carbon dioxide and produces oxygen for homes [89]. While these projects celebrate cyanobacteria's potential, they often lack foregrounding care in human-cyanobacteria relationships.

A care-centered perspective feels especially urgent, given cyanobacteria's largely negative public image. Ironically, they are often associated with water pollution due to their role in harmful algal blooms (HABs) [90]. However, blaming these microbes for "pollution" is deeply anthropocentric and overlooks the relational dynamics between human activities and cyanobacteria proliferation. Blooms are typically caused primarily anthropogenic activities such as agricultural runoff, wastewater, and industrial discharges [91]. By blaming cyanobacteria, the public discourse obscures the human cause and excuses humans for our responsibility in mitigating the pollution.

These entangled relationships between humans and cyanobacteria provide

rich motivation for my research. Cyanobacteria are ancient ancestors to all life, intimately linked to humans through every breath. Yet, human arrogance and ignorance perpetuate misconceptions about their role in the planet's ecology and climate health. By highlighting the inherent interdependence between humans and cyanobacteria, my research seeks to explore alternative relationships through the design of living artefacts that center care for cyanobacteria and their ecosystems.

REFERENCES

[1] P. J. Crutzen. “The “anthropocene””. In: *Earth system science in the anthropocene*. Springer, 2006, pp. 13–18.

[2] A. L. Tsing. *The mushroom at the end of the world: On the possibility of life in capitalist ruins*. Princeton University Press, 2015.

[3] R. R. Nelson. “Capitalism as an engine of progress”. In: *Research policy* 19.3 (1990), pp. 193–214.

[4] D. J. Haraway.“Making Kin: Anthropocene, Capitalocene, Plantationocene, Chthulucene”. In: *Staying with the Trouble: Making Kin in the Chthulucene*. Duke University Press, 2016, pp. 99–103. ISBN: 9780822362142. URL: http://www.jstor.org/stable/j.ctv11cw25q.9 (visited on 09/03/2024).

[5] M. Tironi, M. Chilet, C. U. Marín, and P. Hermansen. *Design for more-than- human futures: Towards Post-Anthropocentric Worlding*. Taylor & Francis, 2023.

[6] R. Braidotti. “Posthuman humanities”. In: *European Educational Research Journal* 12.1 (2013), pp. 1–19.

[7] L. Forlano. “Posthumanism and Design”. In: *She Ji: The Journal of Design, Economics, and Innovation* 3.1 (2017), pp. 16–29. ISSN: 2405-8726. DOI: https://doi.org/10.1016/j.sheji.2017.08.001. URL: https: //www.sciencedirect.com/science/article/pii/S2405872616300971.

[8] C. DiSalvo and J. Lukens. “22 Nonanthropocentrism and the Nonhuman in Design: Possibilities for Designing New Forms of Engagement with and through Technology”. In: *From Social Butterfly to Engaged Citizen: Urban Informatics, Social Media, Ubiquitous Computing, and Mobile Technology to Support Citizen Engagement* (2011), p. 421.35

[9] N. Smith, S. Bardzell, and J. Bardzell. “Designing for Cohabitation: Naturecultures, Hybrids, and Decentering the Human in Design”. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI ’17. Denver, Colorado, USA: Association for Computing Machinery, 2017, pp. 1714–1725. ISBN: 9781450346559. DOI: 10.1145/3025453.3025948. URL: https://doi.org/10.1145/3025453.3025948.

[10] R. Clarke, S. Heitlinger, A. Light, L. Forlano, M. Foth, and C. DiSalvo. “More-than-human participation: design for sustainable smart city futures”. In: *Interactions* 26.3 (2019), pp. 60–63.

[11] E. Giaccardi and J. Redström. “Technology and more-than-human design”. In: *Design Issues* 36.4 (2020).

[12] P. Coulton and J. G. Lindley. “More-Than Human Centred Design: Considering Other Things”. In: *The Design Journal* 22.4 (2019), pp. 463–481. DOI: 10.1080/14606925.2019.1614320. eprint: https://doi.org/10.1080/14606925. 2019.1614320. URL: https://doi.org/10.1080/14606925.2019.1614320.

[13] D. Haraway. *The companion species manifesto: dogs, people, and significant otherness*. Prickly Paradigm Press, 2003.

[14] D. J. Haraway. *When species meet*. Vol. 3. University of Minnesota Press, 2008.

[15] K. Barad. Meeting the universe halfway: Quantum physics and the entanglement of matter and meaning. Duke University Press, 2007.

[16] M. P. de la Bellacasa. *Matters of Care: Speculative Ethics in More than Human Worlds*. Minneapolis: University of Minnesota Press, 2017.

[17] P. C. De Ruiter, V. Wolters, and J. C. Moore. *Dynamic food webs: multispecies assemblages, ecosystem development and environmental change*. Elsevier, 2005.

[18] E. Kirksey. *Emergent Ecologies*. Duke University Press, 2015. ISBN: 9780822360179. URL: http://www .jstor.org /stable/j.ctv11cvzzq (visited on 09/03/2024).

[19] G. Deleuze. *A thousand plateaus: Capitalism and schizophrenia*. University of Minnesota Press, 1987.

[20] J. Liu, D. Byrne, and L. Devendorf. “Design for collaborative survival: An inquiry into human-fungi relationships”. In: *Conference on Human Factors in Computing Systems Proceedings* 2018, April (2018). DOI: 10.1145/3173574.3173614.

[21] J. Zhou, R. Kim, Z. Doubrovski, J. Martins, E. Giaccardi, and E. Karana. “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/10.1145/3563657.3596132.

[22] D. Chen, Y. a. Seong, H. Ogura, Y. Mitani, N. Sekiya, and K. Moriya. “Nukabot: Design of Care for Human-Microbe Relationships”. 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: 10.1145/3411763.3451605. URL: https: //doi.org/10.1145/3411763.3451605.

[23] G. Oktay, Y. Ikeya, M. Lee, B. Barati, Y. Lee, Y. Chen, L. Pschetz, and C. Ramirez-Figueroa. “Designing with the More-than-Human: Temporalities of Thinking with Care”. In: *Companion Publication of the 2023 ACM Designing Interactive Systems Conference*. DIS ’23 Companion. Pittsburgh, PA, USA: Association for Computing Machinery, 2023, pp. 104–106. ISBN: 9781450398985. DOI: 10 .1145 /3563703 .3591462. URL: https: //doi.org/10.1145/3563703.3591462.

[24] G. Oktay, M. Lee, B. Barati, and R. Wakkary. “Caring through: Engaging with temporality of care in more-than-human design”. In: Proceedings of the Halfway to the Future Symposium. HttF ’24. Santa Cruz, CA, USA: Association for Computing Machinery, 2024. ISBN: 9798400710421. DOI: 10.1145/ 3686169.3686211. URL: https://doi.org/10.1145/3686169.3686211.

[25] M. L. J. Søndergaard and N. Campo Woytuk. “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/10.1145/3544548.3581083.

[26] W. Myers. *Bio design*. Museum of Modern Art, 2012.

[27] E. Karana, B. Barati, and E. Giaccardi. “Living Artefacts: Conceptualizing Livingness as a Material Quality in Everyday Artefacts.” In: *International Journal of Design* 14.3 (2020), pp. 37–53. URL: http://www.ijdesign.org/ index.php/IJDesign/article/view/3957/923.

[28] Living Things. URL: http://www.livingthings.us.

[29] E. G. Groutars, C. C. Risseeuw, C. Ingham, R. Hamidjaja, W. S. Elkhuizen, S. C. Pont, and E. Karana. “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*. CHI ’22. New Orleans, LA, USA: Association for Computing Machinery, 2022. ISBN: 9781450391573. DOI: 10.1145/3491102.3517713. URL: https: //doi.org/10.1145/3491102.3517713.

[30] R. Kim, C. Risseeuw, E. G. Groutars, and E. Karana. “Surfacing Livingness in Microbial Displays: A Design Taxonomy for HCI”. 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 .3581417. URL: https: //doi.org/10.1145/3544548.3581417.

[31] F. Bell, M. Ramsahoye, J. Coffie, J. Tung, and M. Alistar. “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/10.1145/3563657.3596133.

[32] N. Campo Woytuk, F. Bell, J. Y. Park, M. Alistar, and M. Balaam. “A Plurality of More-than-Humanness: Feminist Speculations for Designing with the Vaginal Microbiome”. In: *Proceedings of the Halfway to the Future Symposium*. HttF ’24. Santa Cruz, CA, USA: Association for Computing Machinery, 2024. ISBN: 9798400710421. DOI: 10.1145/3686169.3686170. URL: https://doi.org/10.1145/3686169.3686170.

[33] V. Mironov, T. Trusk, V. Kasyanov, S. Little, R. Swaja, and R. Markwald. “Biofabrication: a 21st century manufacturing paradigm”. In: *Biofabrication* 1.2 (2009), p. 022001.

[34] A. D. Ginsberg and N. Chieza. “Other Biological Futures”. In: *Journal of Design and Science* (2018).

[35] Y. Chen and L. Pschetz. “Microbial Revolt: Redefining biolab tools and practices for more-than-human care ecologies”. In: *Proceedings of the CHI Conference on Human Factors in Computing Systems*. CHI ’24. Association for Computing Machinery, 2024. ISBN: 9798400703300. DOI: 10.1145/3613904.3641981. URL: https://doi.org/10.1145/3613904.3641981.

[36] J. Kim, R. Kim, J. Martins, and E. Karana. “Becoming microbes: An approach to cultivating microbial sensibilities in biodesign”. In: *Proceedings of DRS*. Design Research Society, June 2024.

[37] F. Bell and L. Buechley. “Directions for Degradation: Multispecies Entangle- ments with 3D Printed Biomaterials”. In: *Proceedings of the Halfway to the Future Symposium*. HttF ’24. Santa Cruz, CA, USA: Association for Computing Machinery, 2024. ISBN: 9798400710421. DOI: 10.1145/3686169.3686181. URL: https://doi.org/10.1145/3686169.3686181.

[38] E. G. Groutars, R. Kim, and E. Karana. “Designing living artefacts for multispecies interactions: An ecological approach”. In: *International Journal of Design* 18.2 (2024), pp. 59–78.

[39] E. Karana, H. McQuillan, V. Rognoli, and E. Giaccardi. “Living artefacts for regenerative ecologies”. In: *Research Directions: Biotechnology Design* 1 (2023), e16. DOI: 10.1017/btd.2023.10.

[40] V. Shiva. *Staying alive: Women, ecology, and survival in India*. Vol. 84. Kali for Women New Delhi, 1988.

[41] V. Shiva and M. Mies. *Ecofeminism*. Bloomsbury Publishing, 2014.

[42] K. Warren. *Ecofeminist philosophy: A western perspective on what it is and why it matters*. Rowman & Littlefield, 2000.

[43] V. Plumwood. *Feminism and the Mastery of Nature*. Routledge, 2002.

[44] J. C. Tronto. *Moral Boundaries: A Political Argument for an Ethic of Care*. New York, NY: Routledge, 1993.

[45] D. Curtin. “Toward an Ecological Ethic of Care”. In: *Hypatia* 6.1 (1991), pp. 60–74. DOI: 10.1111/j.1527-2001.1991.tb00209.x.

[46] D. J. Haraway. “Speculative Fabulations for Technoculture’s Generations: Taking Care of Unexpected Country”. In: *The Multispecies Salon*. Duke University Press, Sept. 2014. ISBN: 978-0-8223-5610-3. DOI: 10.1215/9780822376989-016. URL: https://doi.org/10.1215/9780822376989-016.

[47] T. van Dooren. *Flight Ways: Life and Loss at the Edge of Extinction*. Columbia University Press, 2014.

[48] B. Mollison. *Permaculture: A Designer’s Manual*. Sisters Creek/Tasmania: Tagari Publications, 1988.

[49] G. Burnett and J. Mars. *Permaculture: a beginner’s guide*. Spiralseed, 2008.

[50] M. Mellor. *Feminism and ecology: an introduction*. NYU Press, 1997.

[51] D. B. Rose. “Multispecies knots of ethical time”. In: *Environmental Philosophy* 9.1 (2012), pp. 127–140.

[52] R. J. King. “Caring about nature: Feminist ethics and the environment”. In: *Hypatia* 6.1 (1991), pp. 75–89.

[53] A. M. Jaggar. “Feminist Ethics”. In: *The Blackwell Guide to Ethical Theory*. Ed. by H. L. -. Blackwell, 2000, pp. 433–460.

[54] M. Murphy. “Unsettling care: Troubling transnational itineraries of care in feminist health practices”. In: *Social Studies of Science* 45.5 (2015), pp. 717–737. ISSN: 03063127. URL: http://www.jstor.org/stable/43829053 (visited on 09/12/2023).

[55] A. Mol, I. Moser, and J. Pols. *Care in practice: On tinkering in clinics, homes and farms*. transcript Verlag, 2010.

[56] C. Key, F. Browne, N. Taylor, and J. Rogers. “Proceed with Care: Reimagining Home IoT Through a Care Perspective”. 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 .3445602. URL: https: //doi.org/10.1145/3411764.3445602.

[57] K. Helms and Y. Fernaeus. “Troubling Care: Four Orientations for Wickedness in Design”. In: *Proceedings of the 2021 ACM Designing Interactive Systems Conference*. DIS ’21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 789–801. ISBN: 9781450384766. DOI: 10.1145/3461778.3462025. URL: https://doi.org/10.1145/3461778.3462025.

[58] N. Campo Woytuk, J. Y. Park, J. Maslik, M. Ciolfi Felice, and M. Balaam. “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/10.1145/3563657.3595966.

[59] J. Bardzell, S. Bardzell, and A. Light. “Wanting To Live Here: Design After Anthropocentric Functionalism”. 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: 10.1145/3411764.3445167. URL: https://doi.org/10.1145/3411764. 3445167.

[60] C. Mancini, J. van der Linden, G. Kortuem, G. Dewsbury, D. Mills, and P. Boyden. “UbiComp for Animal Welfare: Envisioning Smart Environments for Kenneled Dogs”. In: *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. UbiComp ’14. Seattle, Washington: Association for Computing Machinery, 2014, pp. 117–128. ISBN: 9781450329682. DOI: 10.1145/2632048.2632073. URL: https: //doi.org/10.1145/2632048.2632073.

[61] R. Armstrong. “Biodesign for a culture of life: Of microbes, ethics, and design”. In: *Lockton, D., Lenzi, S., Hekkert, P., Oak, A., Sádaba, J., Lloyd, P. (eds.) Spain: DRS2022: Bilbao*, 2022, pp. 1–20. DOI: 10.21606/drs.2022.144. URL: https://doi.org/10.21606/drs.2022.144.

[62] T. van Dongen. Spark of Life. 2016. URL: https://www.teresavandongen. com/Spark-of-Life.

[63] T. van Dongen. Ambio. 2014. URL: https://www.teresavandongen.com/ Ambio.

[64] W. E. Connolly. “The ‘New Materialism’ and the Fragility of Things”. In: Millennium 41.3 (2013), pp. 399–412. DOI: 10.1177/0305829813486849. eprint: https://doi.org/10.1177/0305829813486849. URL: https: //doi.org/10.1177/0305829813486849.

[65] J. Bennett. *Vibrant Matter: A Political Ecology of Things*. Duke University Press, 2010.

[66] K. Barad. “Posthumanist performativity: Toward an understanding of how matter comes to matter”. In: *Signs: Journal of women in culture and society* 28.3 (2003), pp. 801–831.

[67] E. Karana, B. Barati, V. Rognoli, A. Zeeuw Van Der Laan, et al. “Material driven design (MDD): A method to design for material experiences”. In: *International Journal of Design* 9.2 (2015), pp. 35–54.

[68] H. McQuillan and E. Karana. “Conformal, Seamless, Sustainable: Multimorphic Textile-forms as a Material-Driven Design Approach for HCI”. 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 .3581156. URL: https: //doi.org/10.1145/3544548.3581156.

[69] B. Barati, E. Karana, S. Pont, and T. van Dortmont. “Living Light Interfaces —An Exploration of Bioluminescence Aesthetics”. In: *Designing Interactive Systems Conference 2021*. DIS ’21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 1215–1229. ISBN: 9781450384766. DOI: 10.1145/3461778.3462038. URL: https://doi.org/10.1145/3461778.3462038.

[70] E. Giaccardi and E. Karana. “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.

[71] E. Karana, E. Giaccardi, N. Stamhuis, and J. Goossensen. “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.

[72] B. Barati, E. Giaccardi, and E. Karana. “The Making of Performativity in Designing [with] Smart Material Composites”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI ’18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–11. ISBN: 9781450356206. DOI: 10.1145/3173574.3173579. URL: https://doi.org/10.1145/3173574.3173579.

[73] K. Barad. “On Touching—the Inhuman That Therefore I Am”. In: *differences* 23.3 (Dec. 2012), pp. 206–223. ISSN: 1040-7391. DOI: 10.1215/10407391-1892943. URL: https: //doi.org/10.1215/10407391-1892943.

[74] K. Helms. “Designing with care: Self-centered research for interaction design oth-

erwise". PhD thesis. KTH Royal Institute of Technology, 2023.

[75] R. Aghighi. Biogarmentry. 2019. URL: https://www.royaaghighi.com/ biogarmentry.html.

[76] D. Easterly, M. Kenyon, and T. Rorke. "Tardigotchi: Considerations on Pets and Digital Simulations". In: *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '11. Easterly. Funchal, Portugal: Association for Computing Machinery, 2010, pp. 391–392. ISBN: 9781450304788. DOI: 10.1145/1935701.1935795. URL: https://doi.org/10.1145/1935701.1935795.

[77] R. Cavicchioli, W. J. Ripple, K. N. Timmis, F. Azam, L. R. Bakken, M. Baylis, M. J. Behrenfeld, A. Boetius, P. W. Boyd, A. T. Classen, and et al. "Scientists' warning to humanity: Microorganisms and climate change". In: *Nature Reviews Microbiology* 17.9 (2019), pp. 569–586. DOI: 10.1038/s41579-019-0222-5.

[78] S. F. Gilbert. "Holobiont by birth: Multilineage individuals as the concretion of cooperative processes". In: *Arts of living on a damaged planet. Ghosts of the anthropocene ; Monsters of the anthropocene*. Minneapolis: University of Minnesota Press, 2017.

[79] P. Pataranutaporn, A. Vujic, D. S. Kong, P. Maes, and M. Sra. "Living Bits: Opportunities and Challenges for Integrating Living Microorganisms in Human-Computer Interaction". In: *Proceedings of the Augmented Humans International Conference*. AHs '20. Kaiserslautern, Germany: Association for Computing Machinery, 2020. ISBN: 9781450376037. DOI: 10.1145/3384657. 3384783. URL: https://doi.org/10.1145/3384657.3384783.

[80] A. H. Knoll. *Life on a Young Planet: The First Three Billion Years of Evolution on Earth: The First Three Billion Years of Evolution on Earth*. Princeton University Press, 2015.

[81] B. A. Whitton. *Ecology of cyanobacteria II: their diversity in space and time*. Springer Science & Business Media, 2012.

[82] P. Lindberg, S. Park, and A. Melis. "Engineering a platform for photosynthetic isoprene production in cyanobacteria, using Synechocystis as the model organism". In: *Metabolic Engineering* 12.1 (2010), pp. 70–79. ISSN: 1096-7176. DOI: https://doi.org/10.1016/j.ymben.2009.10.001. URL: https: //www.sciencedirect.com/science/article/pii/S1096717609000871.

[83] S. A. Angermayr, K. J. Hellingwerf, P. Lindblad, and M. J. Teixeira de Mattos. "Energy biotechnology with cyanobacteria". In: *Current Opinion in Biotechnology* 20.3 (2009). Energy biotechnology / Environmental biotechnology, pp. 257–263. ISSN: 0958-1669. DOI: https://doi.org/10. 1016/j.copbio.2009.05.011. URL: https://www.sciencedirect.com/ science/article/pii/S0958166909000706.

[84] M. Mehdizadeh Allaf and H. Peerhossaini. "Cyanobacteria: model microorganisms and beyond". In: *Microorganisms* 10.4 (2022), p. 696.

[85] P. Agarwal, R. Soni, P. Kaur, A. Madan, R. Mishra, J. Pandey, S. Singh, and G. Singh. "Cyanobacteria as a Promising Alternative for Sustainable Environment: Synthesis of Biofuel and Biodegradable Plastics". In: *Frontiers in microbiology* 13 (2022), p. 939347.

ISSN: 1664-302X. DOI: 10.3389/fmicb.2022.939347. URL: https://europepmc.org/articles/PMC9325326.

[86] D. Datta, E. L. Weiss, D. Wangpraseurt, E. Hild, S. Chen, J. W. Golden, S. S. Golden, and J. K. Pokorski. “Phenotypically Complex Living Materials Containing Engineered Cyanobacteria”. In: *bioRxiv* (2023), pp. 2023–01.

[87] I. Jang, J. Park, Y. Son, J. Min, W. Park, and C. Yi. “Photosynthetic living building material: Effect of the initial population of cyanobacteria on fixation of CO2 and mechanical properties”. In: *Construction and Building Materials* 396 (2023), p. 132218.

[88] R. Hazekamp. *Unlearning Photography: Listening to Cyanobacteria*. 2024. URL: https://helsinkiphotomedia.aalto.fi/wp-content/uploads/2024/04/94_Hazekamp_Risk_UnlearningPhotography.pdf.

[89] C. Pasquero and M. Poletto. BioBombola by ecoLogicStudio lets you grow an algae garden in your own home. 2020. URL: https://www.designboom.com/ design/biobombola-ecologicstudio-algae-garden-home-06-08-2020/.

[90] H. W. Paerl, R. S. Fulton III, P. H. Moisander, and J. Dyble. “Harmful freshwater algal blooms, with an emphasis on cyanobacteria.” In: *The Scientific World Journal* 1 (2001), pp. 76–113.

[91] K. G. Sellner, G. J. Doucette, and G. J. Kirkpatrick. “Harmful algal blooms: causes, impacts and detection”. In: *Journal of Industrial Microbiology and Biotechnology* 30 (2003), pp. 383–406.

3 Crafting Relations in the Shared Habitat

"Knowing does not come from standing at a distance and representing the world but rather from a direct material engagement with the world."

—Karen Barad

This chapter sets a base for the overarching goal of multispecies relationality and flourishing in biodesign, and explores the significance of the careful consideration of how the shared habitat between humans and living organisms is biologically, ecologically and socially (re)configured in designing living artefacts. The chapter consists of several research activities that collectively refine my research direction.

I begin with a review of literature and practice on designing with living organisms, emphasizing the relational stance of humans and living artefacts in biodesign. I propose the biodesign continuum, a framework that sees the design of living artefacts as an iterative process of configuring and reconfiguring shared habitats. Along biodesign continuum, I offer a taxonomy of digital tools for crafting habitabilities of living artefacts, providing a practical resource for biodesigners to develop tools for mutual thriving.

This exploration highlights the potential of dynamic materials in crafting relations in the shared habitat, and direct material engagement. It refines the focus on crafting care relations within shared habitats and a critical gap: the role of materiality in fostering care relations. Then, I address the challenges of designing care relations with microbes, particularly due to their microscopic scale and distinct temporalities.

Then, through first-person lived experiences with two microbes, Pyrocystis lunula and Spirulina platensis, I identified the need for timely recognition of microbial living states, a challenge of noticing microbial temporalities, and the tension between prescriptive care instructions and the unpredictable realities of everyday life and living systems. The chapter concludes by speculating on how materiality can be explored to address the challenges and tensions, envisioning imaginary living artefacts that foster alternative human-microbe care relations.

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3.1. DESIGNING WITH LIVING ORGANISMS: FROM FUNCTIONALITY TO RELATIONALITY

Over the last decade, there's a growing interest in both design and human-computer interaction (HCI) fields, in designing with living organisms, aiming to achieve novel interaction possibilities and ecological impact in everyday artefacts. The basic idea is that artefacts, machines and computers can be complemented or ultimately substituted by living organisms [2–4]. The endeavors can be concluded as several design and HCI paradigms, including DIYbio, biological HCI, bioart and biodesign. As they present exciting opportunities for design and HCI advancement, approaches with more reflective nature emerged to examine our relationships with living organisms and the broader nature. A posthumanist paradigm manifests itself in sustainable and critical HCI, which has great impact on approaches and practices of designing with living organisms. The views on the relationships between humans and these living organisms have been evolving towards notions and theories with ecological, social and ethical implications. First, let’s take a look at different streams of research and development within the design and HCI research communities that contributed to understanding of these aspects.

3.1.1. DIYBIO

Associated with hacker cultures, DIYbio promotes tinkering and open access to biological tools, protocols, and knowledge outside of professional settings [5]. The outcomes of this work, manifested as hybrid assemblages of living and digital materials, have been used to foster public discourse around the emerging intersections of biology and computation, and to surface unexplored design opportunities and challenges [5]. In addition, a growing number of DIY toolkits [6, 7] and open source platforms have been introduced [8–10] that enable non-technical users to experiment with living organisms, such as yeast and bacteria, and integrate them into art and design materials (e.g., [11–13]. Well-known examples of such DIYbio tools are platforms such as DIYbio (https://diybio.org), labs such as Genspace (https://www.genspace.org), OpenPCR (https://openpcr.org), and hardware such as OpenLH [14] and Pearl Blue Transilluminator [10, 15].

3.1.2. BIOLOGICAL HCI

The aim of a body of research in the HCI community is to examine the roles living organisms could play in human-computer interaction design. The challenges and opportunities brought about by complex control systems and observable patterns of behavior in response to the environment have made living organisms a fascinating topic for HCI and interaction design [2]. For example, researchers explored the potentials of microorganisms for designing living material interfaces as sensing device [16, 17], ambient displays (e.g., [18–20]), and for visualization of personal and social practices (e.g., [6, 21–23]), and novel media for interactive artefacts [24, 25].

Within this body of research, some have proposed taxonomies. Cheok et al. identified four archetypes for using microorganisms for artistic and display purposes: *Inherent Phenomenon, Semantic Interaction, Functional Transformation and Transgenic Display* [18]. They also proposed a taxonomy of six design dimensions: *organism, interface, control, time constant, DNA alteration, and semantics* [18]. Parkes et al. [2] identified areas where living organisms have been integrated into everyday life, including information display, fabrication, energy production, materials, and components.

In parallel, HCI researchers proposed conceptual frameworks intended to inform HCI researchers who are new to the possibilities and challenges of working with living organisms. For example, Pataranutaporn et al. provide an analysis of research projects that integrate microorganisms as part of the computing system, and propose the notion of *Living Bits* to challenge the traditional boundaries between biological cells and computers [26]. Merritt et al. define *Living Media Interfaces* (LMIs) "as interfaces that incorporate living organisms and biological materials to take advantage of their qualities to enable different forms of interaction between humans and digital systems." [4] (p. 3) From this perspective, they pointed out the shared characteristics between LMIs and physical computing systems, and identified different elements for designing with LMIs (pp. 13-15).

This type of work initially emphasizes the functional potential of living organisms, as fascinating materials that could offer tangible and sustainable alternatives to digital computing systems. The relationship between humans, technologies, and biological materials [4] usually appears to be one-way. Biological materials are approached mainly in terms of exploitation rather than a mutual relationship of cohabitation.

3.1.3. BIOART AND BIODESIGN

Artists and designers have been experimenting with living organisms for sustainable material and production alternatives as well as for artistic and critical purposes [27, 28]. This line of work has been documented and curated in important exhibitions such as *Alive: New Design Frontiers at Central Saint Martins* (2013) and *La Fabrique du Vivant | Designing the Living* at the Centre Pompidou (2019). Bioart examples include the culture of microbes for creating visual imagery (e.g., *Contagion*, bacteria billboard [29]); *Antibiotic-responsive Bioart* [12], sensory stimuli (e.g., *Microbial Perfume* [30]), autonomous robots (e.g., *Caravel* [31]), musical composition (e.g., *Biota Beats* [32]).

Building on a relatively established field of biofabrication in biomedical science and engineering [33–35], today, potential applications of biodesign vary from organ printing and energy production (biofuels from algae, for example), to animal-free leather-like materials (such as MycoWorks' fungi-based leather [36]), biodegradable living coffin (*Living Cocoon* [37]) and regenerative photosynthetic materials [38].

Camere and Karana provided a systematic overview of design practices at the seams of biology and design, ranging from the speculative to the commercial, into four categories [39]: (1) augmented biology, in which designers seek the re-engineering of cells to design new biological organisms that can help us cope with contemporary societal challenges, such as famine, diseases, and energy shortages [27, 40]; (2) biodesign fiction, in which designers speculate on the implications of biotechnological futures before they happen through scenarios or prototypes [27, 41];(3) growing design, which is characterized by hands-on practice and focused on the development of novel materials for product design [42–44]; and (4) digital biofabrication [42], in which the researchers emphasize the unique couplings of biological tools with advanced computer technologies in biodesign [45–47]. Materials and artefacts have been co-created with digital technologies and biological processes, e.g., *Mycelium Chair* [48] and *Silk Pavilion* [49].

To avoid the pitfalls of biodesign, such as possibly failing to challenge modern economic paradigms or deliver social transformation, or leading to unexpected ecological problems, Ginsberg and Chieza suggested that future biodesign should help us identify new diverse biological, ecological, and social models that are equitable for all biologies, not just for humans and a few monoculture crops [50]. Recently, Karana et al. introduced the notion of *Living Artefacts*—artefacts that can sense, grow, adapt, and eventually die, and are ecologically and socially embedded in everyday life [51]. Based on an extensive and in-depth analysis of existing living artefacts, the work proposes three biodesign principles as fundamental loci of designing with livingness as a material quality: *living aesthetics* (i.e., the way humans experience the type, degree, and duration of change in a living artefact over time), *mutualistic care* (i.e., the reciprocal and evolving relationship between humans and living artefacts), and *habitabilities* (i.e., the various ways in which living and non-living entities condition the livingness of an artefact). The conceptual framework encourages a new biological thinking that facilitates "non-hierarchical alliances, symbiotic attachments, and the mingling of creative agents (human and non-human alike) in everyday life." (p. 49)

3.1.4. CRITICAL AND SUSTAINABLE HCI

Another body of work, affiliated with critical and sustainable HCI, calls for careful consideration of the ethical imperative and the significance of involving other-than-human species (e.g., animals, plants, fungi, bacteria and more) in HCI [52, 53]. Researchers engage in critical and sustainable HCI research through the lens of specific practices or with a focus on particular organisms. Part of this work has mainly considered insects, plants, and animals in built environments [54–58]. For example, in Frankjaer's project *Cyborganic*, digital tools enable human beings to experience insects' perspectives in urban environments [59]. Some HCI researchers consider plants' well-being, implicating directions like HCI for plants dissemination [60]. Informed by feminist scholarship notions such as *collaborative survival* and *arts of noticing* [61], Liu et al. have proposed speculative digital tools for detecting mushrooms in the wild, and for spores analysis [52]. Other HCI researchers discuss how new technologies which integrate microorganisms, such as bacteria and slime mold, will increasingly rely on symbiotic relationships between the user and organisms that participate in interactive systems (e.g., *Nukabot* [62]).

These works initiate a rich vocabulary reflecting posthumanist values and decentering humans to describe how HCI frames itself in relation to global ecological and societal challenges [63–66]. These positions foreground the need for other-than-human stakeholders such as insects, plants, and microorganisms to come into play.

In conclusion, the endeavours of designing with living organisms to date depict a continuum of more-than-human relationships spanning single, one-way functional to a multispecies web of symbiotic relationships. Encouragingly, this continuum reflects a historical trend where more and more designers and researchers are reflective of their approaches and dedicated to fostering multispecies flourishing in the relational web of planetary survival. Under this background, my research positions itself towards a relational perspective in designing with living organisms. Particularly, it aims to explore how care relations between humans and living organisms could be seamlessly incorporated into the artefacts situated in the everyday doings and happenings. Initially inspired by the notion of *habitabilities* [51], in the next section, I will first explore crafting of relations in the shared habitats between humans and living artefacts, for multispecies flourishing.

3.2. CRAFTING HABITABILITIES: A RELATIONAL PERSPECTIVE

The environment in which living organisms thrive is called a habitat. When designing a living artefact, the initial step involves materializing a habitat by identifying the essential elements, their relations, and the compositions necessary for the organism's survival and well-being. Technically, designing such habitats requires a deep understanding of the energy conservation mechanisms vital for primary metabolic processes like photosynthesis, aerobic and anaerobic respiration, and fermentation [67, 68]. Depending on the specific organism, sources such as light, oxygen, carbon, and nitrogen may be crucial—or unnecessary—for maintaining life.

Karana et al. introduced the notion of *habitabilities* as a key biodesign principle for creating living artefacts, emphasizing the ecological and social considerations essential for crafting multispecies habitats [51]. Habitability refers to "the way the human body and other living and non-living entities condition the livingness of an artefact" throughout its lifespan (p. 48). This principle is critical for transitioning from an exploitative approach to one that enables and facilitates multispecies cohabitation [69].

Building on this notion, **I propose that a relational perspective in designing living artefacts requires carefully crafting the relations between these artefacts and humans within their shared habitat, considering biological, ecological, and social aspects to ensure the mutual well-being of both.** Although microbial well-being lacks a formal definition, here, I define "mutual well-being" or "mutual thriving" as *a state of thriving characterized by a reciprocal relationship between the living artefact and the human*. In this state, the living entities fulfill their metabolic needs, maintain vitality and stability, creating a balanced and sustainable relationality.

In order to understand "how" to craft the relations within the shared habitat, I explore tools that can support that in biodesign. To do so, I first gather living artefact cases to date, examine and reinterpret the digital tools used in designing the (shared) habiat. I offer biodesigners a taxonomy of digital tools for crafting habitabilities of living artefacts. Second, I identify the under-explored potential of dynamic materials for offering alternative tools, suggesting that this area holds significant promise for crafting relations in the shared habitat.

3.2.1. THE RICH TAPESTRY OF DIGITAL TOOLS—A TAXONOMY

Digital technologies have played a pivotal role in advancing our understanding of the biological world [70]. In biodesign, digital tools are frequently integrated with biological systems to aid in the biofabrication of artefacts [39]. Beyond their technical applications, digital tools are also crucial in fostering communication, cooperation, and emotional connections between living organisms and humans.

Through my review of various living artefact cases, I have identified the extensive use of digital technologies in both the ecological and social dimensions of habitat crafting. In this section, I provide a comprehensive overview of the roles digital tools play in shaping the habitabilities of living artefacts.

Living Artefact Selection

The cases were collected across multiple existing fields at the intersection of biology, HCI, art, and design, including *biodesign, bioart, DIYbio, biofabrication, biotechnology, sustainable HCI,* and *bioHCI*. These cases include physical artefacts in which (1) living organisms are kept alive in the use time of the artefact and (2) use of a specific digital tool(s) is described as part of the biodesign process, particularly in exploring and crafting the habitabilities of things (both human and other-than-human) which condition the livingness of an artefact. The following keywords were used for case collection: microorganism, microbial, microbes, bacteria, yeast, algae, fungi, biodigital, biodigital fabrication, bio-computation, biological AI, growing materials, and living materials. Google was used as search engine, for searching on websites (research institutes, design related media), in scientific publications, and design exhibitions. A total of 77 cases were gathered. Most cases were selected between April 2020 and September 2020; however, at the time of writing this dissertation, one new case was added. Priority was given to cases that situated artefacts in the everyday context, and

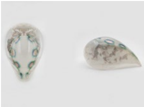
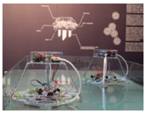
	Image	Description	Digital Tool and Role	Source
1		Vespers III by Neri Oxman and The Mediated Matter Group of MIT Media Lab, a living mask that induce engineered bacteria to produce pigment in response to detected chemicals	Digital Camera for image capture from microscopy Computer Aided Design (CAD) for modelling material behavior	https://www.media.mit.edu/projects/vespers-iii/overview/
2		Genesis Eco Screen by BigRep (www.bigrep.com), a 3D printed installation inhabited by green plants, embedding water supply and a drainage system in the scaffold	Agent-based Modelling on Rhino-grasshopper platform for form finding 3D printing for fabrication the scaffold	https://3dprinting.com/news/genesis-eco-screen-bigrep-creates-biodiversity-habitat/
3		H.O.R.T.U.S XL by ecoLogic Studio, a 3D printed bio installation containing microalgae	3D printing used for fabrication of the scaffold	http://www.ecologicstudio.com/v2/project.php?idcat=7&idsubcat=59&idproj=177
4		Living Tattoo by Liu et al. (2017), MIT, a 3D printed living tattoo that detects chemicals on human skin	3D Bioprinting for direct writing of engineered bacteria cells, signalling chemicals and nutrients	https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201704821
5		Caravel by Ivan Henriques, a self-sustaining environmental robot that cleans water by propelling itself on the water surface	Electronic Components for harvesting electricity produced by bacteria that are living in the water	https://ivanhenriques.com/works/caravel/
6		Living Things by Jacob Douenias, Ethan Frier, and Lena Tesone, an interior lighting installation incorporating microalgae that produces oxygen, food, and fuel through photosynthesis	Semi-automatic photobioreactor designed and embedded for harvesting biomass and regulating biomass volume	http://www.livingthings.us
7		Rafigh by Hamidi and Baljko, a living media display incorporating mushroom growth for showing the frequency of using a therapeutic application by children with disabilities	Microcontroller to control irrigation system, to map mushroom growth to children's use of a therapeutic application	https://dl.acm.org/doi/10.1145/3064663.3064708
8		Living Wall by Danelle Briscoe, University of Texas at Austin, a vertical plant system to maintain biodiversity in a hot and dry environment	Post-installation Building Information Modeling workflow for monitoring the biological species living in the wall; making maintenance and upkeep an interactive experience	https://gispoint.de/fileadmin/user_upload/paper_gis_open/DLA_2020/537690066.pdf
9		Urban Algae Canopy by ecologic Studio, an urban installation that is home to microalgae providing interactive shades for visitors	Sensors and controllers, electronic valves to coordinate the spatial distribution and flow of microalgae according to human position	http://www.ecologicstudio.com/v2/project.php?idcat=3&idsubcat=59&idproj=137
10		Living Light Lamp by Nova Innova and Plant-e, a lamp harvesting energy through the photosynthetic process of plants and metabolism of bacteria	Electronic sensors and controllers, LED mapping the action of caressing (biosensing) to signals for controlling the intensity of light	https://livinglight.info/about/
11		Nukabot by Chen and Seong et al. (2021), a technologically enhanced traditional Japanese wooden bucket used to pickle vegetables using lactic acid bacteria	A combination of sensors, speech recognition and output tool, web data storage, and a digitally controllable blinking plastic eye	https://dl.acm.org/doi/10.1145/3411763.3451605

Figure 3.1.: 11 representative cases of living artefacts in which digital tools are used in crafting their habitability across design time and time of cohabitation

either had been published or exhibited at HCI and design venues (e.g., CHI, DIS, Biofabricate). Thus, the cases concerning biotechnology in medicine and agriculture/food industry (e.g., human tissue engineering, micro-algae food production) were eliminated from the collection. *Eleven* representative cases (figure 3.1) of living artefacts were selected, in which digital tools are used in crafting their habitabilities across both design time and time of cohabitation. The list is not meant to be exhaustive, but representative for the taxonomy themes that I will elaborate in this section.

The analysis of verbal descriptions of the cases identified several key activities that digital tools facilitate in the process of crafting habitabilities in biodesign. These activities include: observing organisms' behavior in artificial habitats; modeling organisms' behavior in response to habitat parameters; form-finding for the physical habitat that accommodates the living organisms; fabricating the physical habitat; depositing cells and chemicals within the habitat; regulating habitat conditions to sustain the organisms' livingness; and interfacing the communication of living states between multi-species.

These activities were then clustered into three pillars: (1) *understanding the habitat*, (2) *embodying the habitat*, and (3) *perpetuating the habitat*. The themes span over a continuous timeframe, referred to as the *biodesign continuum* (figure 3.2), illustrating their mutual connection. Below, I elaborate on each theme, and outline the role of digital tools to crafting habitabilities throughout the biodesign continuum.

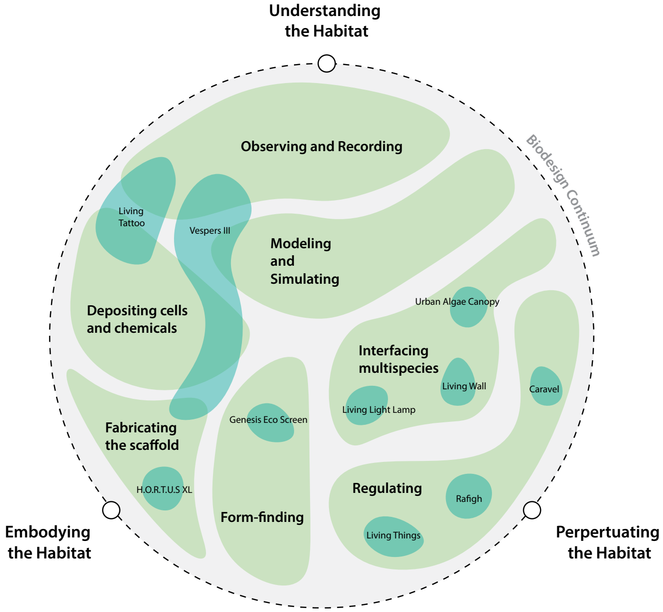


Figure 3.2.: Diagram of the biodesign continuum

Understanding the Habitat

This pillar concerns an understanding of the relations between the elements of a natural or artificial habitat, that is crucial in forming optimal assemblages for living organisms involved in designing living artefacts. To understand involves observing, recording, modelling and simulating these relations between various living and nonliving elements.

Observing and Recording In animal studies and co-living, two well-known tools used to provide real-time data on animals' location are implantable microchips and GPS trackers. The latter, particularly, can provide information on habitability of wildlife and their migration routes, according to which the built environment could be modified (e.g., *Wildlife Crossings* in Banff National Park by Parks Canada) [53]. Besides, diversity of organisms and their distribution in a specific natural area can be observed with remotely controlled technologies. To detect and quantify diverse taxa of bioluminescent organisms off the California coast, scientists use remotely operated vehicles to record and observe in situ [71]. In the design of living artefacts, living organisms are often observed in a controlled environment, using both specialized lab equipment (e.g., microscopes) and DIY devices, (e.g., a shaker for bioluminescent dinoflagellates [24]). An example of the latter is a shaker designed to explore the effect of specific environmental parameters (i.e., three types of kinetic stimuli) on flash qualities of bioluminescent dinoflagellates [24].

A more commonly used technique in observing and recording living organisms' behaviour is digital photography, which can help cultivate designerly sensibility of nature-culture relationships [52], and situational awareness to help understand how the observed organism interacts with its milieu on the micro-level [72]. In biodesign, cameras, digital microscopes, and microtomography are widely used for imaging purposes and providing qualitative data on organisms' growth and other observable behavior (e.g., movement). In *Vesper III*, a mask on which engineered bacteria are inoculated to generate chemical substances useful for humans, time-lapse digital images were taken to document organism response during the incubation hours [46].

Modeling and Simulating Modeling and simulation is a primary technique to create a tractable space [73] for understanding and quantifying biological systems [74]. An example is biologically-informed computer aided design (bioCAD) tools to study and design cell colony behavior across spatial and temporal scales [75]. A frequently implemented bioCAD method is agent-based modeling [76], which has been increasingly applied to model cell colony behaviors as complex systems, such as in *Position-based Dynamic Model* for bacteria [75].

Modeling and simulating can predict, to some extent, biological behaviours in geometrically complex habitats. *Vesper III* instantiates how this informs habitat design by providing understanding on the various elements of the habitat and their intricate relations in a complex geometrical setting (figure 3.3). Biological response (pigment production) in relation to the geometry and spatial-temporal distribution of chemical signals in an object [46] is estimated by a unique computational model tailored to the system in a CAD environment [46].

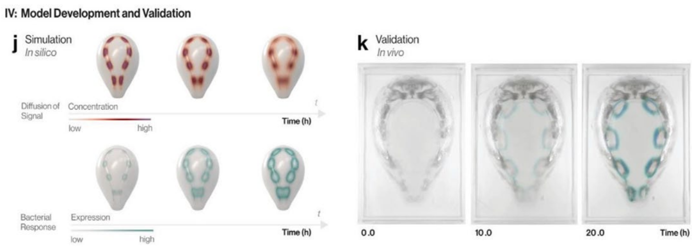


Figure 3.3.: Vespers III: simulation of the various elements of the habitat and their intricate relations in a complex geometrical setting

Embodying the Habitat

The second pillar of the taxonomy concerns an embodiment of an optimal habitat for living organisms' thriving. These habitats, referred to as the "first habitat" [51], provide conditions for living organisms to thrive in the shared habitats with humans (the second habitat). The form of the physical artefact, its material composition, and distribution of cells, nutrients, and sometimes behaviour-inducing chemicals collectively influence the organism's vitality.

Form-finding Form-finding for a habitat involves balancing the living organism's needs with the designer's requirements for functionality and aesthetic expression. In this process, algorithms play a crucial role in determining geometry and material composition [77]. The design and optimization of a habitat's form are typically facilitated by computer-aided design (CAD) tools and parametric design platforms, such as Rhino-Grasshopper, which allow for precise and adaptable configurations.

One notable advancement in computer-aided form finding is the development of agent-based modeling (ABM) methods and software tools. ABM has been widely applied in domain-specific assessments, such as evaluating building performance for fire evacuation or controlling crowd movement [78]. However, its application extends beyond these areas to the design of living artefacts as well. For example, in the creation of the *Genesis Eco Screen*, a green wall designed to support plant growth, ABM was utilized for solar radiation analysis to optimize the form of the artefact according to its specific environment. Additionally, ABM played a crucial role in designing the embedded irrigation channels, ensuring that water was precisely delivered to the plants through an integrated micro-shower mechanism (figure 3.4).

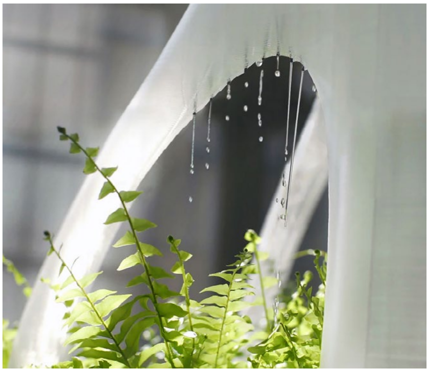


Figure 3.4.: Genesis Eco Screen: embedded micro-shower irrigation channel

Fabricating the Scaffold Scaffold refers to the physical structure where living organisms attach directly in an artefact. Material properties, geometry, porosity, and pore size of a scaffold all contribute efficient cell attachment [79]. In biodesign, a scaffold is typically constructed using digital fabrication tools (e.g., *Mycelium Chair* by Klarenbeek [48] and *Silk Pavilion* [49] developed by The Mediated Matter Group at the MIT Media Lab), where living and digitally designed materials provide each other with structural stability[47].

In *H.O.R.T.U.S XL*, a large scale installation inoculated with microalgae, the scaffold is fabricated with a Fused Deposition Modeling (FDM) 3D printing process (figure 3.5). The artefact's form is informed by biological models of collective coral morphogenesis. The density-value of each bio-pixel is digitally computed in order to maximize incoming light and metabolism of the organism along iso-surfaces [80]. In *Vespers III*, a multi-material inkjet-based 3D printer (Objet Connex500, Stratasys, Rehovot, Israel) was used to fabricate a scaffold for bacteria hydrogel sheet in the form of a mask. The printer delivers hard photopolymer resins to create material structures and a soft material containing chemical solution to stimulate bacterial colour change.

Figure 3.5.: H.O.R.T.U.S XL: fabricated scaffold for microalgae with a FDM 3D printing process

Depositing Cells and Chemicals Cell deposition facilitates the attachment of cells to physical scaffolds, with its efficiency and distribution significantly influencing the scaffold's biological performance and the spatiotemporal pattern generation process [75, 81]. Computer-assisted techniques, such as 3D bioprinting, offer precise control over the positioning of living cells [82], finding applications in areas like drug delivery, tissue engineering, soft actuators, and adaptive building systems [83].

In the realm of living artefact design, bioprinting has been employed not only for depositing living cells but also for integrating chemical signals. A notable example is the *Living Tattoo*, a bioprinted tattoo capable of detecting chemicals on human skin [83]. In this project, 3D bioprinting facilitated the incorporation of multiple chemical-sensing cells and chemical signals onto the surface of a bilayer elastomeric sheet (figure 3.6). While standard 3D printers aren't typically designed for depositing cells and chemicals, they can be modified to perform such tasks. For instance, in the *Vespers III* project, two traditional resins were used to print the physical scaffold. Unconventionally, a third material—the support material usually discarded after printing—was repurposed to encapsulate chemical signals, showcasing innovative use of existing printing technologies.

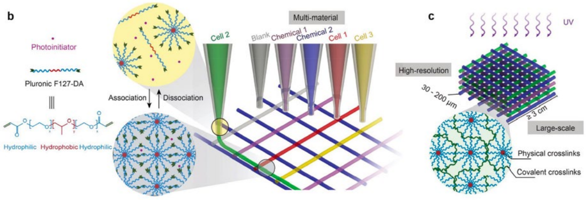


Figure 3.6.: Living Tattoo: incorporation of multiple chemical-sensing cells and chemical signals onto the surface of a bilayer elastomeric sheet

Perpetuating the Habitat

The third pillar focuses on the perpetuation of the habitat, ensuring that the living organism can continue to thrive alongside humans for as long as possible. This involves not only the regulation of environmental conditions but also the ongoing interaction between humans and living artefacts throughout the cohabitation period. By maintaining optimal conditions and fostering a dynamic relationship between all inhabitants, the habitat can support sustained living and mutual well-being over time.

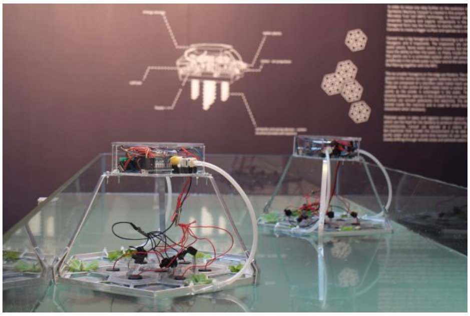


Figure 3.7.: Caravel: continuously seeking out waste (food for microbes) and purify water in a self-sustaining loop

Regulating Conditions In order for living organisms to thrive and perform stably, the internal and external elements of their habitat should be regulated. A well-known instance of digital tools regulating (human) habitats is *Google Nest* learning thermostat, which monitors and adjusts ambient temperature in cooperation with and by learning from people and their daily habits.

Digital tools can facilitate the automated regulation of habitats, aiming to create self-sustaining environments [51] that minimize human intervention. In these systems, habitats are equipped with sensors to monitor the organism's living conditions and states, alongside control units that make decisions and take actions to modify and optimize the environment accordingly. This automation allows humans to adopt a more passive role, driven by the need for precision or convenience. Automated regulation is widely applied in industrial-scale bioprocessing, where fresh medium is added to fermenters or bioreactors, and used medium and cells are harvested automatically. Living artefacts designed to require minimal human intervention leverage the self-regulating capabilities of digital systems. An example of this is *Caravel*, an installation composed of bacteria that autonomously moves on water while consuming and cleaning organic matter. The bacteria on the installation's carbon-brush tentacles convert waste into electricity through their metabolic processes. Digital components harness this electricity to power movement, enabling the installation to continuously seek out waste and purify water in a self-sustaining loop (figure 3.7).

Figure 3.8.: Living Things: maintenance of the microalgae's growth by harvesting excess biomass

Digital tools can also enhance human engagement in the care of living artefacts by facilitating active participation in habitat regulation. One such example is *Living Things*, a domestic lighting installation system where human co-habitants directly contribute to the maintenance of microalgae. In this system, microalgae are housed in glass vessels that share a light source with the human residents. The photobioreactors pump air to mix the liquid culture and allow for the controlled release of excess biomass, which can later be used as agricultural fertilizer or biofuel. By harvesting the excess biomass, humans help prevent sedimentation and attachment to the vessel walls, thus maintaining the microalgae's growth rate and volume [84] (figure 3.8).

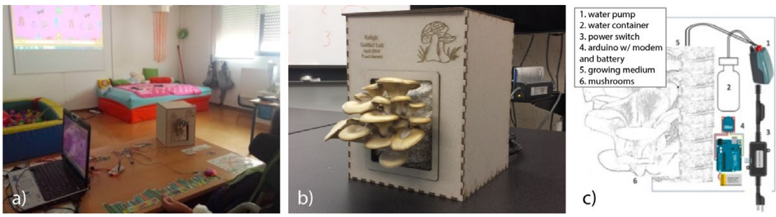


Figure 3.9.: Rafigh: regulation enabled through the mapping of quantitative data from human activities to a habitat condition—water

Another example is *Rafigh* [6], where regulation is enabled through the mapping of quantitative data [4] from human activities, unrelated to the living artefact, to a specific habitat element—water (figure 3.9). In this case, the system controls the water supply to moderate mushroom growth based on children's use of a therapeutic digital application. The more time children spend on the target application, the more water is administered to the mushrooms, promoting their growth. This electronic control system fosters a reciprocal relationship between the mushrooms and the children, using indirect regulation to encourage positive behavioral changes.

Interfacing Multispecies Interfacing how the state of living is being communicated between multispecies (humans and other-than-humans) is of vital importance to ensure the mutual well-being of both. Interfacing the state of living through digital means is a well-established practice, particularly in agriculture, where it has been used for years to maintain optimal conditions for crops. For instance, the *Farmer's Helper*, a chatbot developed by a former engineer in Taiwan, provides crucial information about seasonal crop suitability, alerts farmers to extreme weather conditions, and warns of potential pest infestations [66]. Digital sensing technologies play a key role in enabling plant caretakers to monitor and respond to the needs of their plants. Modern examples include soil testers, such as the Flower Monitor, which provide real-time data on factors like light, water, nutrients, and temperature. This information is relayed to users through smartphone applications, allowing for timely adjustments to the plant's environment and enhancing the overall health and growth of the plants.

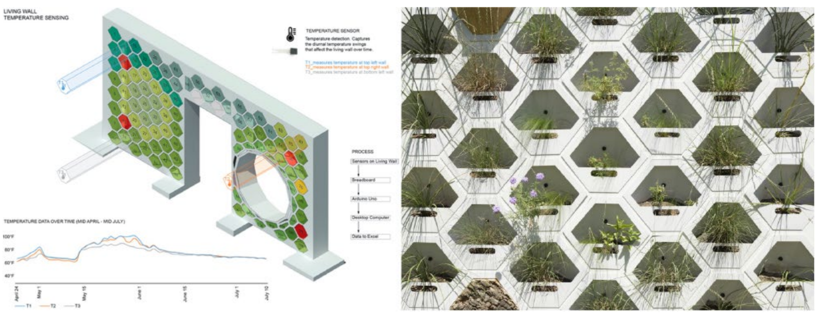


Figure 3.10.: Living wall: remote upkeep and analysis of interactions between the wall's surface, fauna habitats, and the plants it supports

Communication between humans and living artefacts can involve a broader range of species and interactions, particularly with the integration of advanced data technologies. A prime example is the *Living Wall*, a piece of living architecture designed to support specific plants and other species, such as pollinators and songbirds, thereby enhancing biodiversity in hot and dry climates. This project uses a multi-stakeholder monitoring system that enables remote, interactive upkeep (figure 3.10). The system collects and analyzes data on interactions between the wall's surface, fauna habitats, and the plants it supports, taking into account factors like user proximity, daily water distribution, and local temperature values [85]. This data-driven approach not only helps maintain the health of the wall but also ensures that it can adapt to the needs of its diverse inhabitants, fostering a more complex and interconnected ecosystem.

Figure 3.11.: Living Light: lighting up with a human touch, symbolizing a mutualistic care scenario

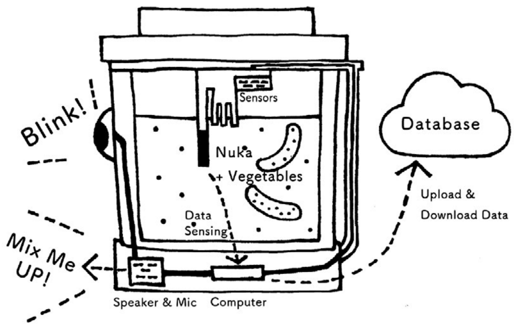


Figure 3.12.: Nukabot: emotional connections between humans and food-fermenting microbes established through a blinking eye and vocal interactions with the artefact

Emotional connections and symbolic relationships among multispecies can be established through technological mediation. An illustrative example is the *Living Light Lamp*, which generates energy using bacteria in soil, powered by organic matter from plant photosynthesis—a process known as a Plant Microbial Fuel Cell [86] (figure 3.11). The well-being of both plants and bacteria is communicated through the intensity of the lamp's light. Here, the plant leaves function as a sensing interface between humans and the living artefact, with digital components processing bioelectrical signals [87]. When humans touch or caress the plant leaves, the interaction symbolizes mutualistic care [51], and the plant's immediate response is expressed through light, mediated by a microcontroller. In another example, *Nukabot* [62], emotional connections between humans and food-fermenting microbes are established through a blinking eye and vocal interactions with the artefact (figure 3.12). These responses are triggered by sensed data and managed by a central computer, creating a more intimate and symbolic relationship between humans and the microbes they cultivate.

3.2.2. UNDER-EXPLORED LANDSCAPE OF DYNAMIC MATERIALS

Digital technologies have woven a rich tapestry in facilitating the crafting of habitat relations, supporting the mutual well-being of humans and living artefacts alike. However, the special attention in design research to physical materials is only emphasized in a few cases. For instance, thin layers of hydrogel, as used in *Living Tattoo* and *Vespers III*, expand the design space by enabling artefacts to be situated in diverse environments, including on the human body. Moreover, one case illustrates the importance of tangible, direct interactions with living organisms. In *Living Light Lamp*, for example, people must caress the plant's leaves to activate the light, cultivating a sense of intimacy and connection with the living organism. While a variety of materials have been employed in embodying habitats, there has been relatively little focus on non-digital technological mediation in crafting relations in the shared habitat. This presents an intriguing space for further exploration.

To address this, I turn my attention to dynamic materials—materials that can be engineered to be active and responsive (figure 3.13). Recent advancements in material science have opened up exciting possibilities for dynamic material behavior [88–95]. These emerging materials fall under various categories, including smart materials [96, 97], programmable materials [98], pneumatics [99, 100], multi-material 3D printing [101], 4D printing [102], mechanical meta-materials [103], biomimetics [88], and kinetic materials [104].

In early 2021, the Royal Society released a report titled *Animate Materials* [105], which delves into the development of man-made materials designed to mimic the behaviors of living systems. These materials are not only self-organizing but also responsive to environmental changes, reacting to stimuli such as water or humidity, temperature, pH levels, light, mechanical deformation, vibration, pneumatic pressure, and electrochemical shifts. The convergence of dynamic

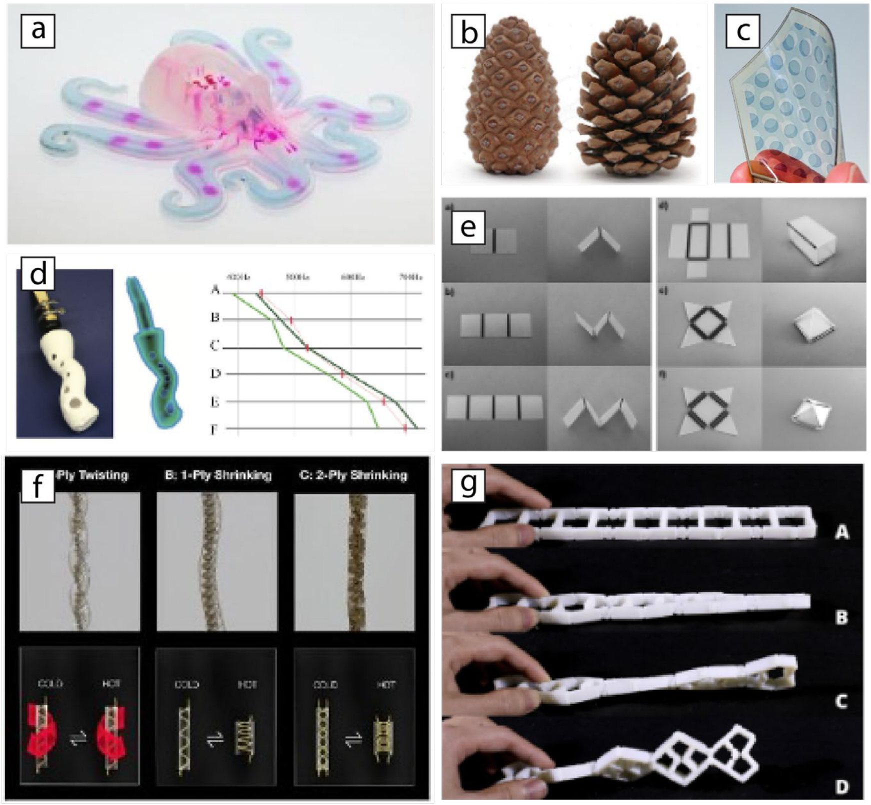


Figure 3.13.: Potential dynamic materials principles that designers could leverage in interfacing living organisms, environments and humans. a) a soft robotic developed with pneumatic stimulation from chemical reactions that generate gas [93]; b) pine cone effect applied in active materials, utilizing differential hygroscopic swelling between two adjacent areas of tissue [95]; c) Electrochromic (EC) display with the capability to change their optical properties through chemical oxidation or reduction when an electric current is applied to it [94]; d) programmable acoustic resonance by tuning internal geometries of the instrument [91]; e) self-folding polymer sheets that Convert light into heat by applying light-absorbing black ink on specific spots on polymer sheets [90]; f) shape memory alloy coil coated with silicone allowing two-way reversible shrinking or twisting behaviors triggered by heat or electrical current [89]; g) auxetic-inspired material structures that can transform into various shapes upon compression [92]

materials with living organisms opens up exciting possibilities.

One notable example is the pneumatic robot described by Wehner et al. [93], which demonstrates how dynamic materials can achieve biomimicry and responsive design. In this case, the robot's movement is powered by chemical reactions that generate gas within its chambers, triggering specific movements as the internal volume and pressure change. This principle could be adapted for habitats housing organisms that naturally produce gas through metabolic activities. Could such a mechanism be harnessed to create a living interface, indicating the organism's life activities and wellbeing to humans?

By leveraging dynamic materials, researchers could develop interfaces between living organisms, their environments, and humans that are not only responsive to changes but also more intuitive, tangible, and intimate than digital counterparts.

In conclusion, the investigation into digital tools and dynamic materials serves three primary purposes for designers: Firstly, it provides a frame of reference that can be used to guide biodesign processes, particularly for supporting the mutual thriving of humans and living organisms involved. Secondly, it offers case-specific practical insights to support emerging biodesign initiatives, such as how certain tools can be deployed. Lastly, it inspires designers in utilization or advancement of tools, as well as development of novel materials, to craft relations in the shared habitats.

3.3. IMPLICATION OF THE REVIEW FOR EXPLORING MORE-THAN-HUMAN CARE IN BIODESIGN

In this section, I discuss the implications of my literature and practice review for exploring more-than-human care in biodesign. Here I elaborate on the conceptual framework of *biodesign continuum* (figure 3.2), emerging research directions of crafting care relations, and emphasize the importance of direct material engagement in that process.

3.3.1. THE BIODESIGN CONTINUUM

Through the lens of digital tools in crafting habitabilities, I introduce a frame of reference for biodesigners to navigate the use of digital tools—the *biodesign continuum*, a loop process in biodesign which encompasses three continuous, intertwined and interconnected stages: *understanding the habitat*, *embodying the habitat*, and *perpetuating the habitat*. This framework underscores the perpetual process of configuring and re-configuring the shared habitat, spanning from the initial design phase to the subsequent co-habitation phase by individuals interacting with the artefact. The "design" of living artefacts is an ongoing process: it is extended from designers to people who live with them. It remains open to change, and over time will adapt to their unique contexts, in a dynamic and unexpected way (see, for example *Urban Algae Canopy*). The continuum highlights the interconnectedness of these pillars, illustrating how actions within one phase can inform and enrich understanding in subsequent phases. For instance, through efforts to perpetuate the habitat, individuals may uncover new insights or experiences that deepen their understanding of the habitat, creating a continuous cycle of learning and adaptation. Designers can use it as a frame of reference in defining the role of technological interventions within their specific projects.

3.3.2. CRAFTING CARE RELATIONS

The review also uncovers that crafting care relations in the shared habitat is essential for mutual thriving. I use a definition from Puig de la Bellacasa's "care relations," *relations where care is done, is actualized, regardless of whether the relations are bound to traditional types*:

> "Care as a doing. Care is a necessary practice, a life-sustaining activity, an everyday constraint. Its actualizations are not limited to what we traditionally consider care relations: care of children, of the elderly, or other “dependents,” care activities in domestic, health care, and affective work—well mapped in ethnographies of labor—or even in love relations."

In living artefacts, care relations can range from self-sustaining habitat where human involvement is reduced to bare minimum, and habitats that require and involve active human participation in everyday interactions. Biologically, a habitat for a living artefact should support the organism's essential processes, like replication and respiration. Studies on Engineered Living Materials (ELMs) offer solutions for self-sustaining habitats, such as resilient living materials built by printing bacterial spores [106]. Digital technologies also show promise in creating self-sustaining environments for living artefacts (see the taxonomy, e.g., *Caravel* and *The Living Things*).

From a social perspective, crafting care relations involves engaging humans in maintaining the metabolic stability of other life forms, creating a livable habitat for both living entities. For instance, the human body may serve as a habitat for a living artefact (see *Vesper III* and *Living Tattoo*), which requires humans to perform care actions to sustain it (see *Rafigh*). While some examples show care actions ambiguously, future design methods should clearly define deliberate care actions and their role in sustaining mutualistic care relations. Designers must consider how the biological and social aspects of habitability are configured from the outset and maintained during cohabitation. Envisioning scenarios of care will be key to this process.

Effective communication between humans and other-than-human entities is also crucial in crafting care relations. Technologies have the potential to support interspecies communication, not only encouraging care actions but also emotional and empathetic connections. This potential is explored in the *Living Light Lamp* (see taxonomy) and projects like *Nukabot* [62], which use cultural references to appeal to caretakers and prompt emotionally-bond care actions.

3.3.3 TOUCHING THE LIVING ARTEFACT: VALUE OF DIRECT MATERIAL ENGAGEMENT IN CARE RELATIONS

My review of tools for crafting relations within shared habitats juxtaposes two groups of technologies: the digital and the material. While inherently different, their boundaries often blur. For instance, materials involved in digital fabrication and human-computer interaction are sometimes considered "digital material" [107–109]. On the opposite, as materials become broad, digital entities such as data and AI are also considered "design materials." [110–113] In embodying habitats, materials can be digitally fabricated, yet retain significant material qualities such as transparency and air-permeability that support livingness. Conversely, the realm of digital technologies has increasingly acknowledged and adopted tangible ways of engaging with them [114].

Drawn by the "lure of touch," in *Matters of Care*, Puig de la Bellacasa discusses the implications of "touch" in care relations [115]. Touch is portrayed as an embodied form of care that extends beyond mere physical contact. It is an ethical act that recognizes the vulnerability and agency of the other, rooted in inherent reciprocity. Care obliges in ways embedded in everyday actions and agencies; it is inherent to relations of interdependency [115]. The discussion here is not about which tools are superior, but rather that, regardless of the tools or their combinations that designers choose, direct material engagement with living artefacts is crucial in fostering care relations within the shared habitat.

While digital technologies are widely accessible and provide a convenient means of coupling living artefacts with enhanced sensing and information display capabilities, I argue that these tools should be directed toward fostering deep emotional and ethical engagements, rather than reducing life and its ecological assemblages to mere data points. One approach to achieve this is by incorporating material engagement in bio-digital artefacts. For example, in the case of *Nukabot*, humans are guided by a digital voice interface to touch and stir the rice bran within the bucket, mixing the fermenting microbial culture. Attention to dynamic materials could further facilitate material engagement—as an integral part of living artefacts, they may inherently align more closely with living organisms exhibiting behaviors, such as slow color and shape changes that are associated with livingness. Owing to their rich texture, sensorial, affective, and performative qualities [116], dynamic materials offer significant sensory value [115] in a mediating role of "touching" the living organism.

3.3.4. MICROBES: CHALLENGES AND OPPORTUNITIES ACROSS SCALES

Out of the eleven cases of the review, nine involve microbes. While microorganisms offer a wealth of possibilities for creating living artefacts—such as changing color displays, oxygen production, water purification, electricity generation, and serving as sources of food and fuel—they also pose significant challenges in fostering relationships with human cohabitants. One of the biggest challenges is their microscopic scale, which makes them less perceivable to the naked eye. This calls for technological mediation to help humans perceive their existence and state of being. For example, the color change in *Vespers III*, the movement of the machine in *Caravel*, and the accumulation of green biomass in *Living Things* all signal activity within the microbial community.

I argue that this kind of noticing, and the cultivation of a "feeling for the organism," [117] is crucial for building care relations with microbes in a shared habitat. This challenge also presents an opportunity for design to further explore and expand this space. The tools presented in the taxonomy, particularly those under *interfacing multispecies*, represent just a small fraction of what designers can achieve in this area. I strongly urge designers to expand on these tools and innovate new ones that enhance our sensibilities to see, listen to, and feel microbes.

3.4. FIRST-PERSON LIVED EXPERIENCES WITH MICROBES

To explore further how it is like to live with and care for microbes, I delved into an auto-ethnography of my own lived experiences with two species of microbes at home for a few months (during the pandemic time when no access to the lab was guaranteed). I was first intrigued by "living glow" of bioluminescent dinoflagellates *Pyrocystis lunula*, and then a "living air purifyer" cyanobacterium *Spirulina palentasis*. During the time, I learnt to take care of them and observed how they changed over time (i.e. living aesthetics). Informed by the material tinkering method [118], I experimented with a few ways to 1) understand their living states better 2) foster direct material engagement with them. This section presents my care practices, observation of their living aesthetics and my tinkering and experiments. In the end I discuss my reflection over this period.

3.4.1. BIOLUMINESCENT DINOFLAGELLATE

Pyrocystis lunula is a species of dinoflagellates, which produce one of the most commonly encountered forms of marine bioluminescence. These single-celled organisms are often referred to as micro-algae or phytoplankton. Among all bioluminescent dinoflagellates, the *Pyrocystis* genus is the most well-known and is often called the "fireflies of the sea," known for their relatively high intensity light emissions [119]. Despite its microscopic size, this tiny organism possesses the incredible ability to produce its own light, creating beautiful patterns and illuminating the ocean waters in which it thrives. When their populations are particularly dense, disturbances in the water can trigger displays of sparkling blue light.

Species of the *Pyrocystis* genus also appear to be the most abundant dinoflagellates in tropical and subtropical areas of the ocean [120]. Through the process of photosynthesis they are able to consumes large amounts of carbon dioxide by converting it into oxygen, making them one of the biggest contributors to the earth's oxygen supply. *Pyrocystis lunula* can be found in various regions of the world, spanning tropical, less tropical and colder waters.

Care

I obtained a *Pyrocystis lunula* culture from a local company in the Netherlands (BioGlow Bioluminescence). They call it bioluminescent algae. The culture came with care instructions (table 3.1).

The culture was housed in a palm-sized plastic spherical container, and it stayed with me in my studio apartment throughout the winter of 2020, during the Netherlands' COVID-19 lockdown. It was a cold, wet winter, and I spent nearly all my time at home with the microbes, 24/7. I kept the container on the only windowsill in the apartment, which faced north. On the rare sunny days, only a sliver of sunlight would reach the window for an hour or two in the morning. I made sure to expose the container to that precious sunlight, though it was scarce. Overall it did not get much nourishment from sunlight, neither did I. The temperature in the apartment was stable, thanks to modern heating. However, sometimes the window sill can get too hot as it's right next to the radiator. Occasionally, I would discard a small amount of liquid from the container, being careful not to lose any of the microbes, and added fresh nutrients. Every evening around eight o'clock, I placed the container in my wardrobe to ensure the microbes were in complete darkness, as I still needed some light for my own activities. Sometimes, I would take the container out, give it a shake, and watch their blue glow—a moment of pure delight and satisfaction.

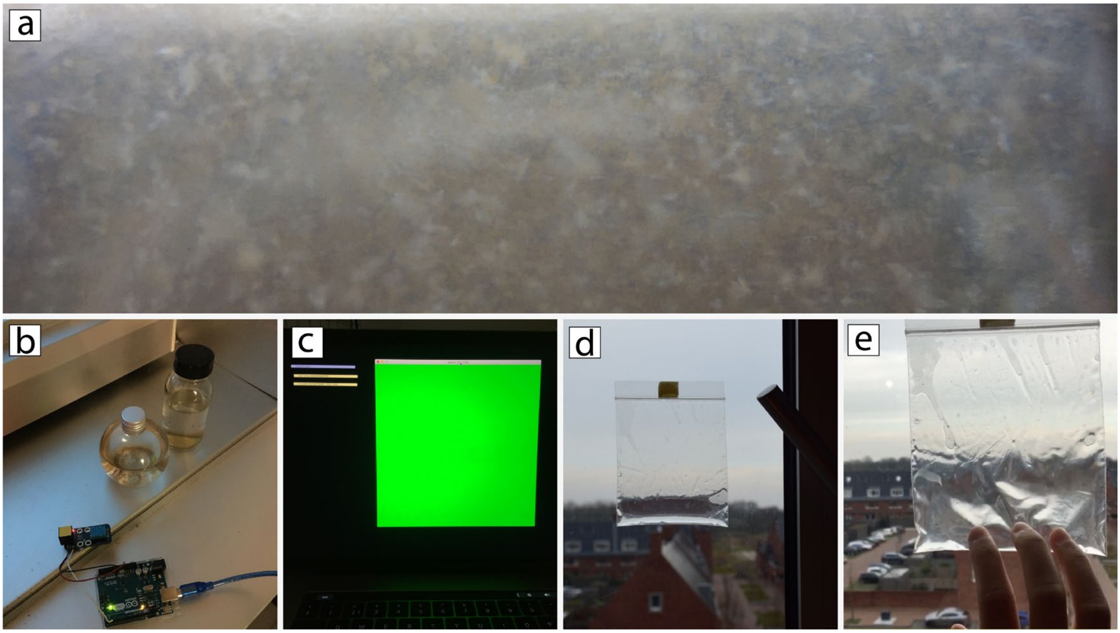


Figure 3.14.: Bioluminescent dinoflagellate *Pyrocystis lunula* under my care at home

Living Aesthetics

The most striking sign of livingness in *Pyrocystis lunula* is its ability to emit a mesmerizing blue light when agitated, creating a stunning display of bioluminescence. The intensity of this glow is directly proportional to the vigor of the shaking—more vigorous movement results in a brighter, more vibrant light.

Care Needs	Description
Arrival	Unpack the algae immediately after arrival. The shipment process may be a bit stressful, so they may need up to a week to recover. It will probably take a few days before you can see them glow.
Temperature	Put the algae at room temperature, between 17 and 24 degrees Celsius. However, they can briefly survive at lower or higher temperatures.
Light	Place your algae in a spot where it is light during the day and dark at night, but never in direct sunlight. Stay at least 2 meters away from windows and room heaters, where the temperature may fluctuate too much. Just like land plants, algae get their energy from light through a process called photosynthesis. Optionally, you can illuminate the algae with a regular light bulb on a timer.
Bioluminescence	The algae glow while you shake them, but only after sunset. They have an internal biological clock, which is based on the light-dark rhythm of the past days. They never glow during the day, not even when you look at them in a dark room. Bioluminescence generally starts about 1 hour after sunset.
Nutrients	The algae can survive for a few months in the provided container, as long as you take good care of them. After a while the nutrients run out, so you need to add extra nutrients to keep the algae alive. We recommend adding nutrients every 2 weeks by replacing at least 10% of the volume with new nutrients.

Table 3.1.: Care instructions given by the seller of the bioluminescent dinoflagellate

After a few shakes, the glow reduced. *Pyrocystis lunula* also follows intriguing temporal rhythms in its bioluminescent activity, adhering to a circadian rhythm. This rhythm was reinforced by my consistent routine of placing the culture in darkness every evening at eight o'clock. Over time, the microbe adjusted, emitting light only after that time. During the day, the microbe appears as beige cellulose fibers suspended in water, quietly unremarkable (figure 3.14, a). Yet, as it grows and reproduces, its nightly glow intensifies, even though the culture seems muted and turbid during the daylight hours, with little to "say."

Experiments

In the first experiment, I focused on creating a system that would notify me of any changes in the microbe's environment, particularly temperature. Using an Arduino board and a temperature sensor, I built a simple circuit to monitor the temperature around the microbe's container (figure 3.14, b). If the temperature remained within the optimal range of 17-24°C, the interface on my laptop screen would turn green; if it fell outside this range, the interface would turn red (figure 3.14, c). I chose my laptop screen as the interface because it was the device I used most frequently and was always in close proximity. This setup allowed me to constantly monitor the microbe's habitat condition without needing to physically check the temperature at the window sill. The microbe was essentially "linked" to the temperature sensor, making it easy to track its environmental conditions no matter where it was placed. In the second experiment, I sought to explore alternative ways of containing the microbe to enable more direct material engagement. Shaking the plastic container was the only method I had been using, but it felt limiting. I started experimenting with materials and objects I found around my kitchen. One container that stood out was a soft, thin zipper bag. When I poured some of the liquid culture into the bag, it immediately felt different—more intimate and tactile. The bag's flexibility and conformability allowed me to attach it to various surfaces, including my arms. I even taped a bag to the window to maximize light exposure on cloudy days (figure 3.14, d). The zipper bag also opened up new possibilities for interaction, enabling finer motions to trigger the bioluminescence, such as tapping with fingers (figure 3.14, e) or stroking with a brush. It turned out to be a playful and engaging experience.

3.4.2. CYANOBACTERIA

Cyanobacteria, often referred to as blue-green algae, are a group of photosynthetic microorganisms that have played a pivotal role in the history of life on Earth. These bacteria are among the oldest life forms, contributing to the Great Oxygenation Event around 2.4 billion years ago, when they began producing oxygen through photosynthesis. This monumental shift enabled the evolution of aerobic organisms, eventually leading to the diversity of life we see today [121]. In our current times, they are primary producers in many aquatic ecosystems, converting carbon dioxide into organic matter and thus acting as a vital carbon sink. This process is essential for regulating atmospheric carbon levels and mitigating climate change.

Spirulina platensis is a species of cyanobacteria that has garnered significant attention due to its nutritional and health benefits [122, 123]. It also has shown promise in various biotechnological applications, ranging from wastewater treatment to the production of biofuels and pharmaceuticals. Moreover, its rapid growth rate and photosynthetic efficiency contribute to its potential as a sustainable resource for addressing global challenges related to food, health, and the environment [124, 125].

Care

I obtained the *Spirulina platensis* culture from an Etsy seller Clemens. The culture arrived with a two-page letter from Clemens, explaining every detail of care for the microbe. I will only quote a few essential ones for the sake of readability and length (table 3.2).

I lived with the *Spirulina platensis* from February to December 2021 (with two batches of purchased cultures), spanning later winter to peak summer. I started to look after the *Spirulina platensis* by following the instruction carefully. The most important thing is to avoid direct sunlight and shake the culture regularly. I replenished nutrients when the color darkened and the culture became less translucent. I housed the culture in multiple glasses with nutrients and placed them on a south-west facing window sill. The winter sunlight was nice, shining mildly into the window onto the cyanobacteria. I would let them have a sun bath. In summer, on the contrary, I needed to constantly adjust the location of the cyanobacteria to avoid the scalding light. During intense sunlight, I moved the cultures to shaded areas and preemptively shaded them with paper when leaving on sunny days. I formed a habit of checking the culture before I went

Care Needs	Description
Arrival	Upon receipt, transfer the algae to a larger container, place it in a warm, bright spot away from direct sunlight, and ensure adequate airflow by loosening the lid. Gently tilt the container at least twice daily to mix the algae. After about 24 hours, they should recover from the transport stress of darkness and limited air exchange.
Temperature	With colder temperatures the metabolism of the algae reduces. This makes the culture more sensitive. Over longer periods under e.g. 18°C this can lead also to the death of the culture.
Light	After dilution, gradually accustom the algae to direct sunlight for faster growth. Begin with short exposures, such as 30 minutes of sunlight followed by 30 minutes of shade, avoiding midday sun. Be cautious, as too much light or overheating can harm the culture. Maintain an optimal growth temperature slightly above 30°C, ensuring it doesn't exceed 40°C, which could be fatal.
Photosynthesis	If all goes well, you'll see air bubbles form when the algae are exposed to bright light—a sign of active photosynthesis and growth. These bubbles push the algae to the surface, so mixing is essential to prevent drying. The algae's movement—rising, bubbling, or sinking—indicates their condition. Rising and bubbling mean they're thriving, while sinking suggests issues like incorrect light, temperature, nutrients, or pH levels.
Nutrients	Upon arrival, dilute the algae to about twice the volume. Mix part of the enclosed nutrient powder (20g per liter) with room-temperature water. Stir well; it won't fully dissolve, which is fine. Let the solution sit for about an hour until it reaches the same temperature as the algae before adding it. Regularly check the algae's density: if a white stick dipped 2 cm into the liquid isn't visible, the culture is too dense and needs dilution.

Table 3.2.: Care instructions given by the seller of the cyanobacteria

out, making sure that it had good conditions. I closely monitored the culture density and adjusted nutrient levels as needed to ensure optimal nourishment.

Living Aesthetics

I observed the most stunning and dynamic movements of the cyanobacteria in the bottle after months of delicate care. The *Spirulina platensis* had grown and multiplied, and the culture had taken on a vibrant dark green hue, a sign of its healthy state. Occasionally, the cells would clump together, floating in the liquid as a gentle reminder to shake the culture. Then, on a bright, warm day in April, I noticed something remarkable: the cyanobacteria had all risen to the surface, forming small bubbles around the floating green mass, just as the care instructions had described (figure 3.15, c). These bubbles, a byproduct of oxygen released during photosynthesis, indicated that the cyanobacteria were actively engaging in the life-sustaining process that kept them healthy.

At times, the cells would attach to the bottle wall, forming a “biofilm” reminiscent of how cyanobacteria cling to rocks and other surfaces in natural water bodies. Occasionally, they would arrange themselves into patterns like spheres or toruses (figure 3.15, b), as if attempting to communicate something. Despite these intriguing behaviors, the exact significance of their movements and what they might be expressing about their needs remained a mystery to me.

At one point, I noticed some bright pink formations in one of the bottles, an occurrence that even confused my microbiologist colleague during the time. We couldn’t identify or explain what these pink spots were or why they had appeared. This unexpected mystery added another layer of complexity and intrigue to the cyanobacteria, reminding me of the unpredictability and richness inherent in working with microbes.

Experiments

As I became increasingly curious about their timely message, and intrigued by the bubbles, my first experiment aimed to visualize real-time oxygen generation by the cyanobacteria (figure 3.16). I attached a soft silicone rubber membrane to the bottle, anticipating that it would bulge as oxygen was released. This idea was partially inspired by the pneumatic robotics I mentioned earlier in my discussion of dynamic materials. I set up a timelapse video next to the bottle, documenting the membrane’s rising and falling throughout the day, from 8 am to 4 pm. The results were surprisingly clear: the membrane rose and fell three

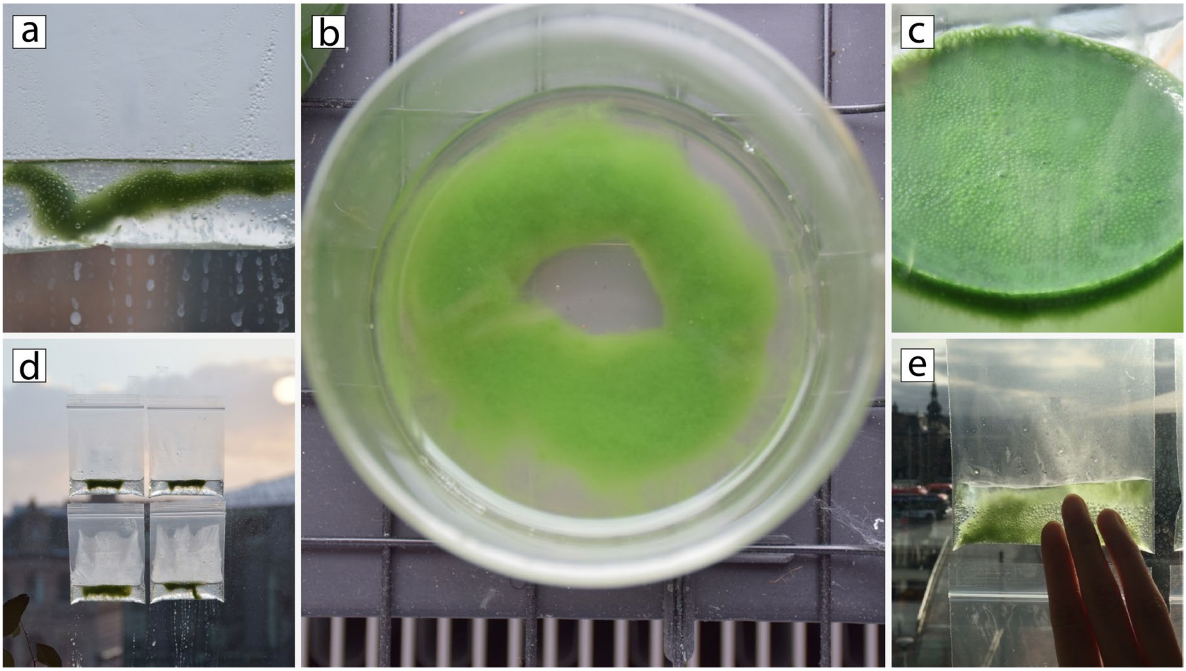
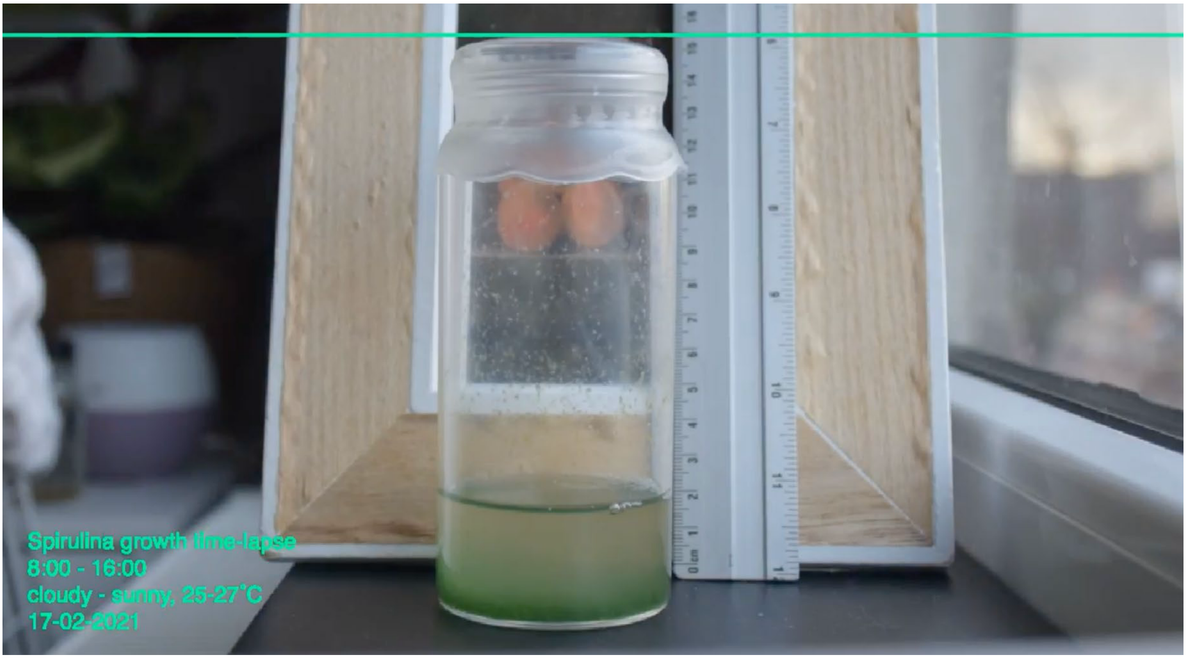


Figure 3.15.: Cyanobacteria spirulina platensis under my care at home
Figure 3.16.: My first experiment aimed to visualize real-time oxygen generation by the cyanobacteria



times during the day. It appeared as though the cyanobacteria were "breathing." However, when I discussed this idea with the microbiologist, he immediately suggested that the effect was likely caused by something else, doubting that the cyanobacteria could produce enough oxygen to cause such noticeable changes. While I didn't investigate further to determine the exact cause, this experiment opened up new possibilities for me. It helped me to imagine about how design could help us understand our living cohabitants in real-time through dynamic material changes.

In the second experiment, much like my earlier work with bioluminescent dinoflagellates, I sought to explore alternative habitats that would foster more direct material engagement with the cyanobacteria culture. My first attempt involved using a ziplock bag. I attached it to my window to maximize sunlight exposure during a rainy winter day (figure 3.15, a, d). To ensure sufficient air exchange, I opened the bag a few times each day. After just a few hours, I noticed a significant number of air bubbles forming inside the bag (figure 3.15, e). I was tempted to tap on the bag to break the bubbles, releasing the oxygen into the atmosphere. The following day, the cyanobacteria clumped together in a linear shape, reminiscent of a "caterpillar." A few days later, I observed something even more intriguing: in the evening, the cyanobacteria in two separate bags had formed identical crescent shapes. I was amazed by this series of changes—not only by the visibility of oxygen production but also by how the simple change of habitat facilitated new ways of engagement with the culture.

The next material I explored was a combination of paper and hydrogel, using spinach puree as a bio-safe substitute for cyanobacteria in this phase of experimentation. This was very much a process of "thinking through making," where ideas and possibilities emerged through hands-on exploration. The technique I employed is common in molecular gastronomy, where I jellified the spinach puree onto the surface of papers. Guided by the feel of the materials, I created various patterns and shapes, taking advantage of the paper's flexibility—it could be easily folded, rolled, or attached to different surfaces. For instance, I wrapped one of these paper creations around a hanging plant pot, introducing new relations between the living and nonliving elements in the space. This approach not only diversified my relationship with cyanobacteria, making it more accessible and transformable, but it also fostered new connections within the habitat, bridging between living organisms and other artefacts.

I experimented with paper forms as the cyanobacteria's alternative habitats, attaching them to various places of my home, exploring ways of situating and interacting with them differently.

3.4.3. REFLECTION AND DISCUSSION

In this section, I reflect on my lived experiences with the cyanobacteria and outline a few avenues for research and design.

Beyond Care Instructions

Both microbes came with detailed care instructions, yet I found that many aspects remained vague or too rigid, which do not capture fully care practices in real life context. For instance, the cyanobacteria sometimes floated to the surface without any accompanying air bubbles, which puzzled me. To clarify, I reached out to Clemens, the seller, for further advice. He explained that the rise and fall of the algae, as well as their tendency to clump together, are influenced by numerous factors, and it's unrealistic to expect visible oxygen bubbles all the time. The key takeaway was the complexity of these parameters, which made it difficult, if not impossible, to fully decipher the phenomena I observed.

Clemens suggested that I regularly stir the culture or consider using an automated bubbling machine to maintain optimal conditions. Intrigued by the idea, I experimented with a bubbling machine designed for aquariums in a small batch of the culture. Unfortunately, this attempt proved unsuccessful, as the cyanobacteria in that batch eventually died—they didn't respond well to the machine. This experience taught me that even with detailed instructions and well-intentioned experimentation, managing a living system can be incredibly complex. The environment's intricacies can render both guidelines and prior experience ineffective, highlighting the need for a more organic and adaptable approach to care.

Cohabiting with microbes involves unforeseen tensions. During the summer of 2021, I traveled outside the Netherlands for more than a month to visit my family in China. Before leaving, I diluted the cyanobacteria culture and distributed it across several bottles, storing them in shaded areas to ensure they received minimal light. My intention was to keep their growth at a moderate rate without exhausting the available nutrients. However, upon returning home after my vacation, I found most of the cultures had turned yellowish-brown—a clear sign of lifelessness. It had been an unusually hot summer, and with all windows closed, the temperature in my south-facing apartment likely soared beyond what the cyanobacteria could tolerate. My desire to take a break at home conflicted with my wish to keep the cultures alive. Fluctuations in environmental factors like light intensity or temperature, though often tolerable or resolvable for human comfort, can have a profound impact on the well-being of microbes. Conversely, the constant attention and adjustments required to meet the needs of these organisms can disrupt human comfort or personal agendas. Navigating these complexities suggests that living artefacts may need to "negotiate" with their human cohabitants, fostering interactions that bring attention to their needs.

Microbe Temporalities as a Challenge in Care

My experiences highlight the importance of understanding microbe well-being states in cultivating care towards microbes. The light emission of bioluminescent dinoflagellates at night gives an indication of my care efforts over the past days. Similarly, the changing colors of cyanobacteria over time serve as indicators of the quality of care provided in the preceding days and weeks. However, I experienced a "time lag" between noticing their living states in the moment they needed the care. This time lag hinders my timely care actions, leaving their needs for care unattended. My experiment amplifying cyanobacteria's oxygen generation provides an alternative way of noticing their metabolic activities, as observable changes it more perceivable. This reinforces the earlier discussion that such noticing is essential for building care relations with microbes. As temporal changes in living aesthetics signal the organism's "well-being or struggle," [51] failing to attune to their temporalities may hinder timely care. This insight drove me to explore alternative ways to attune to microbe temporalities, making us more capable to understand their expression of living states in time.

Materiality of Living Aesthetics and Alternative Habitats

To understand the microbe's habitat conditions, such as temperature, digital sensors and displays, as in my first experiment with bioluminescent dinoflagellates, offers a convenient and efficient method. However, this approach also created a sense of "disconnection" between the microbe and myself, as it replaced the need to observe the culture with my own eyes. In contrast, my attempts to visualize cyanobacteria's oxygen generation through rubber inflation brought a different experience. Capturing the microbe's unique aesthetics directly, through the subtle rise and fall of the membrane, felt intimate, poetic, and mindful—qualities that appealed to me through material tinkering, and that I aim for in fostering care relations with microbes. Unlike digital displays that might substitute or abstract microbial processes, this method amplified the inherent aesthetic of oxygen generation, allowing the microbe's natural materiality to be the primary focus.

I also explored alternative habitats, such as a soft, transparent, and thin bag, which triggered a variety of interactions with the microbes. Some interactions were related to care, like tapping the bag to ensure the cyanobacteria didn't clump together, thereby promoting adequate nutrient and air exposure for each cell. Some were functional, such as agitating the bioluminescent dinoflagellate to elicit its glow. Others suggested scenario of mutualistic care, such as openning the bag to allow oxygen to come out and carbon dioxide to go in. These alternative habitats underscored the significant impact of material qualities, like softness and thinness, on my felt experiences and care practices for the microbes. The materiality of microbial living aesthetics and the habitats elicited both actions of maintenance and new caring affection (the feeling of intimacy), opening up an exciting and under-explored landscape at the intersection of materiality and care design. The following section will open up a design space by imagining this potential, offering initial explorations and insights on how these concepts can be conceptually implemented.

Scientific Engagement for Understanding Microbes

My lived experiences highlighted the need for deeper scientific engagement to better understand microbes. For instance, my experiment on the "breathing" of *Spirulina platensis* left me frustrated, as I found no evidence supporting my hypothesis that it indicated the organism's photosynthesis, rendering my discussions with scientists inconclusive. While the exploratory and intuitive approach yielded valuable contextual insights and reflections, it also raised questions that required answers through lab-based experiments. This realization motivated me to delve further into scientific understanding of cyanobacteria and quantitative characterization as complementary to my other ways of understanding them.

3.5. ENVISIONING MATERIALITY IN CARE RELATIONS

In earlier sections, I refined my research focus to explore materiality and its influence on care relations within shared habitats involving living artefacts. Having seen "what's out there" with previous research, this section, on the contrary, delves into speculation focusing on how material could facilitate noticing and attuning to microbial temporalities, and caring for microbes in living artefacts. By using the term "materiality," I emphasize the importance of material qualities of all living and nonliving entities involved in designing care for living artefacts, including those of materials, digital technologies and living beings.

I present and discuss a series of imaginary living artefacts containing photosynthetic microbes that emerged early in the research process. These conceptual creations do not intend to be technically feasible, but serve as bridge towards my later design experiments. They open up diverse care relations between human and the microbe, and identify technical challenges. Four themes of care relations were generated. Below I outline the themes with a representative artefact under each theme.

3.5.1. IMAGINARY ARTEFACTS AND CARE RELATIONS

Artefact 1

The first artefact is a living hat with photosynthetic microbes embedded in its brim. To nourish the microbe with sunlight, the person needs to wear it under indirect sunlight regularly. When worn under sunlight, if the temperature on the brim exceeds a certain level, the microbes and the material of the hat trigger an assertive animation, causing the brim to fall down. This obstructs the wearer's vision, prompting them to stop and seek shade for the hat. This living hat embodies the first theme, where **individuals are compelled to adjust their activities to accommodate the needs of the artefact.** These artefacts employ a coercive approach, strategically designed to induce behavioral changes in their caretakers, in this example, avoiding excessive sunlight.

Artefact 2

The second artefact is a living windmill toy, with photosynthetic microbes embedded on the fantails. To play with the toy, individuals should activate its spinning by blowing towards it. The breath contains a higher concentration of carbon dioxide than the atmosphere, which boosts the microbe's photosynthesis. This results in the circulation of air, which, containing carbon dioxide, creates a higher concentration around the living organism, serving as a carbon source. In this theme, **care actions manifest as an unintended outcome or using the artefact for its other functions, in this example, a toy for play.**

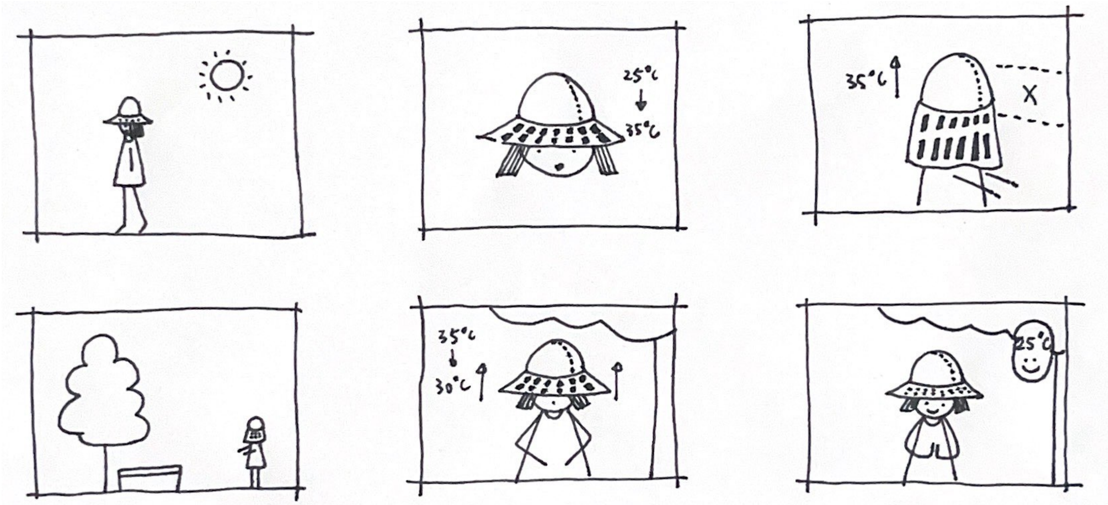
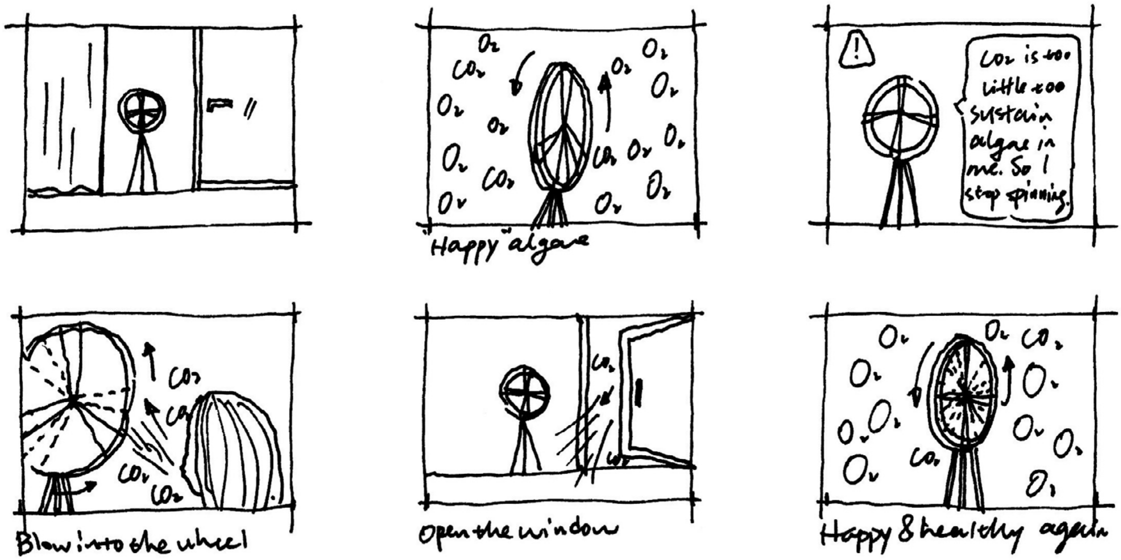


Figure 3.17.: Scenario of wearing the living hat, where the wearer is prompted to adjust their behavior to create more optimal habitat conditions for both themselves and the microbe.

Figure 3.18.: Scenario of playing with the living windmill toy, where the player blows towards it to play, whilst offering habitat element to the microbe



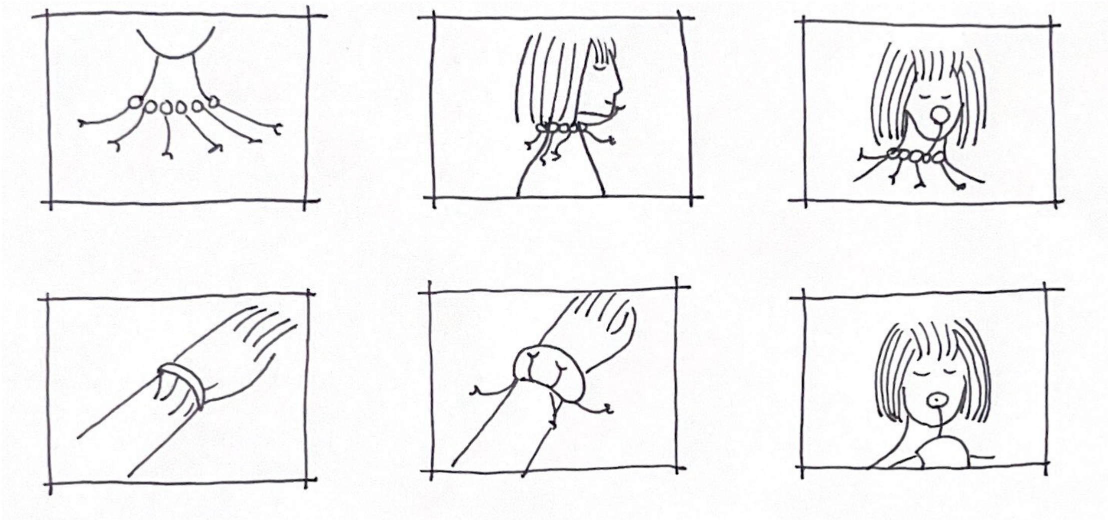
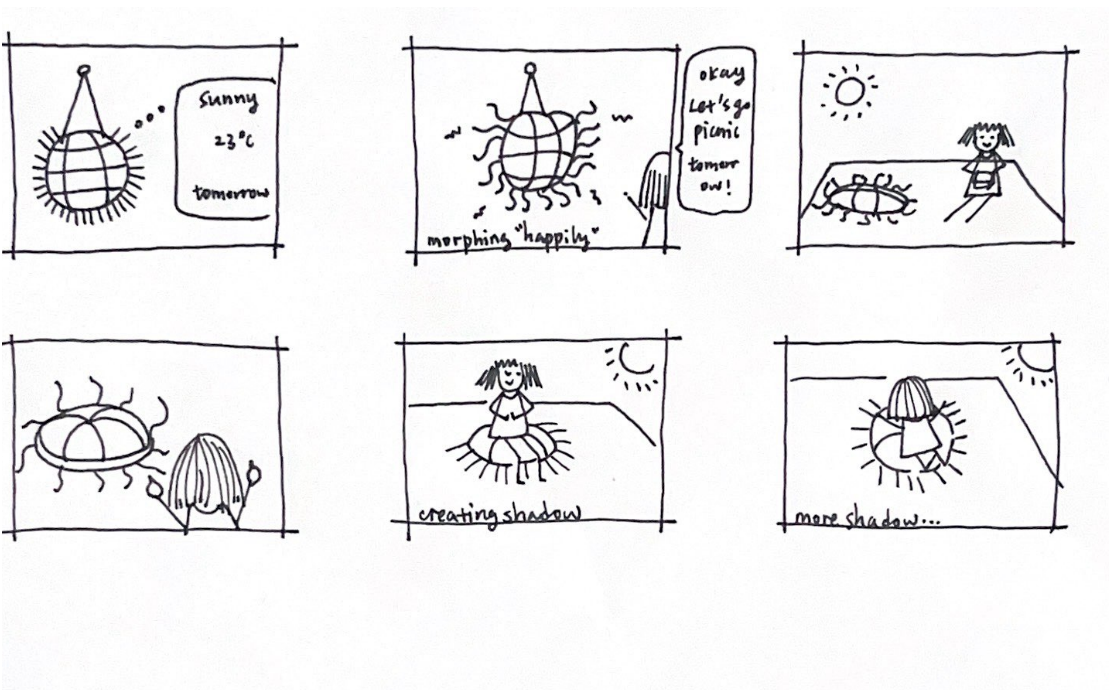


Figure 3.19.: Scenario of wearing the living jewelry, where the wearer's body provides the habitat for the microbe, whilst the microbes' presence influences the wear's identity

Figure 3.20.: Scenario of an outing with the living puff, where the puff's changing form offers new affordances, encouraging the wearer to engage in caregiving actions.



Artefact 3

The third artefact is living jewelry, including a necklace and a bracelet, made of soft materials that house microbes. These microbes thrive on human breath: humidity and other gases. When the microbes require more air, the material inflates and changes shape, enhancing the jewelry's flamboyance and making the wearer more noticeable in social settings. This transformation encourages the wearer and others to observe the change and provide timely breaths to the microbes. The artefact illustrates the third theme, where **the human body becomes a habitat for living artefacts, and the organisms' presence influences the wearer's identity.**

Artefact 4

The fourth artefact is a living puff, where photosynthetic microbes are housed inside the puff body. In sunny weather, the puff subtly encourages its companions to venture outdoors for fresh air and sunlight by waving with its "tentacles." Once outside, it reminds of sunlight intensity by inflating, transforming into a comfortable seat. Observing this change prompts individuals to sit atop the artefact, shielding it from excessive sunlight while enjoying its cushioned support. In the concluding theme, **the artefact invites for care performance by presenting new affordances to individuals, who reciprocate by providing optimal habitat conditions while utilizing it**. This symbiotic relationship between people and the artefact fosters mutual support and well-being for both parties.

3.5.2. DISCUSSION

Technical Challenges

The imaginary concepts highlight a few technical challenges involved in both biological and material processes. The first challenge lies in the bio-compatibility of the artefacts to the microbes. Microorganisms typically thrive in wet environments [126], while the components of the artefacts involved in animation typically favor dry conditions. Merging these disparate environments presents challenges, especially at a microscopic and scale, such as the microbe and the human body scales. Second, all artefacts involves dynamic material processes directly triggered by microbes' biological processes. Whilst digital sensors can detect minute changes from microbes [52, 62, 127], using materials that respond to external changes often require substantial stimuli to display visible changes. As an initial step towards integrating them, identifying a feasible material is crucial.

Re-animating Microbes without Animism

The concept of envisioning materiality in caring for microbes involves what Puig de la Bellacasa describes as "reanimating" microbes within living artefacts—altering the imaginaries of microbes by developing a sense of shared aliveness [128]. In human-computer interaction, animism is often employed as a strategy to enhance the perception of agency in objects. Researchers suggest that animism can contribute significantly to ubiquitous computing, where objects with designed behaviors evoke a sense of autonomy, intention, personality, and inner life [129]. Marenko and van Allen propose *animistic design* as an uncertainty-driven strategy to reimagine human–machine interactions as a dynamic interplay between human and nonhuman agents [130]. They argue that designers should seek a "native" form of animism that aligns with the technology's inherent function and "personality," such as unpredictability. However, I deliberately avoid animism or anthropomorphism as strategies for reanimating microbes. This decision is not only because humans inherently perceive inanimate objects as agents [131], even when these objects do not resemble humans or living beings, but also because I believe that embracing the inherent living aesthetics of microbes, which arise from their metabolic processes, can cultivate a deeper sensibility toward microbes, fostering greater understanding and connection.

Towards Reciprocal and Socially-attuned Care Relations

Through the speculation, I refined my positionality in what kind of care relations I aim to design for. The imaginary artefacts explored how care relations can be an integral part of social practices or encouraging certain practices. For instance, in *Artefact 4*, a simple picnic on a sunny day is not just a commonly-practiced leisure activity for the human but also becomes a care practice, providing much-needed essential sunlight "bath" to photosynthetic microbes. Here my goal is to explore how such human practices and novel care practices can mutually support each other and can be socially-attuned. Through thinking with these care relations, I come to realize that this care relation can foster the mutual well-being of both the human and the microbes embedded in living artefacts through encouraging certain daily routines, communal activities and rituals. In these scenarios, microbes take on the role of "subalterns," [132] wsubtly influencing human behaviors and ways of living. This approach fosters reciprocal and socially-attuned care relations with microbes beyond mere caregiving as a task. For example, in Artefact 3, microbes become integral to the wearer's identity, inviting consideration of how living artefacts can catalyze nuanced changes in social dynamics and power relationships with microbes.

3.6. CONCLUSION

Each section of this chapter has progressively shaped my research direction. The literature review of historical efforts in designing with living organisms revealed a growing trend towards a relational perspective—seeing humans and other beings as interconnected and interdependent within a web of symbiotic relations. Through this lens, I introduced the concept of a *biodesign continuum*: understanding, embodying, and perpetuating the habitat; and I offered a taxonomy of digital tools for crafting habitatbilities, of living artefacts, in biodesign. This biodesign continuum emphasized both the biological and socio-ecological configuration and reconfiguration of elements within shared habitats. I highlighted crafting care relations as key avenues for fostering mutual well-being with living artefacts, and the importance of materiality in this process.

My first-person experience of living with microbes shed light on the unanticipated tensions that arise when human and microbial well-being must coexist within a shared environment. This experience suggested that designers should explore more organic and adaptable approaches to care, with a particular emphasis on noticing more-than-human temporalities. Finally, the imaginary artefacts envisioned how materiality can be harnessed in crafting care relations, and helped me to refine my positionality towards reciprocal and socially-attuned care relations.

Moving forward, the next chapter will further explore a research question generated through and shaped by this chapter, which focuses on designing with temporal dissonance between humans and microbes in living artefacts, crafting with dynamic materials interface, and imagining alternative human-microbe relationships that are reciprocal and socially-attuned.

REFERENCES

[1] J. Zhou, B. Barati, E. Giaccardi, and E. Karana. “Habitabilities of living artefacts: A taxonomy of digital tools for biodesign”. In: *International Journal of Design* 16.2 (2022), pp. 57–73. DOI: 10.57698/v16i2.05. URL: https://doi.org/10.57698/v16i2.05.

[2] A. Parkes and C. Dickie. “A biological imperative for interaction design”. In: *CHI’13 Extended Abstracts on Human Factors in Computing Systems*. 2013, pp. 2209–2218.

[3] P. Pataranutaporn, A. Vujic, D. S. Kong, P. Maes, and M. Sra. “Living Bits: Opportunities and Challenges for Integrating Living Microorganisms in Human-Computer Interaction”. In: *Proceedings of the Augmented Humans International Conference*. AHs ’20. Kaiserslautern, Germany: Association for Computing Machinery, 2020. ISBN: 9781450376037. DOI: 10.1145/3384657. 3384783. URL: https://doi.org/10.1145/3384657.3384783.

[4] T. Merritt, F. Hamidi, M. Alistar, and M. DeMenezes. “Living media interfaces: a multi-perspective analysis of biological materials for interaction”. In: *Digital Creativity* 31.1 (2020), pp. 1–21. ISSN: 17443806. DOI: 10.1080/14626268. 2019.1707231.

[5] S. Kuznetsov, A. S. Taylor, T. Regan, N. Villar, and E. Paulos. “At the seams: DIYbio and opportunities for HCI”. In: *Proceedings of the Designing Interactive Systems Conference*. 2012, pp. 258–267.

[6] F. Hamidi and M. Baljko. “Rafigh: An Edible Living Media Installation”. In: *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction*. TEI ’14. Munich, Germany: Association for Computing Machinery, 2014, pp. 345–346. ISBN: 9781450326353. DOI: 10.1145/2540930.2555209. URL:https://doi.org/10.1145/2540930.2555209.

[7] P. Washington, K. G. Samuel-Gama, S. Goyal, and I. H. Riedel-Kruse. “Bioty: A cloud-based development toolkit for programming experiments and interactive applications with living cells”. In: *bioRxiv* (2017), p. 236919.89

[8] P. Fernando. “Tools for Public Participation in Science: Design and Dissemination of Open-Science Hardware”. In: *Proceedings of the 2019 on Creativity and Cognition*. 2019, pp. 697–701.

[9] P. Fernando and S. Kuznetsov. “OScH in the Wild: Dissemination of Open Science Hardware and Implications for HCI”. In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 2020, pp. 1–13.

[10] S. Kuznetsov, A. S. Taylor, T. Regan, N. Villar, and E. Paulos. “At the Seams: DIYbio and Opportunities for HCI”. In: *Proceedings of the Designing Interactive Systems Conference*. DIS ’12. Newcastle Upon Tyne, United Kingdom: Association for Computing Machinery, 2012, pp. 258–267. ISBN: 9781450312103. DOI: 10.1145/2317956.2317997. URL: https://doi.org/10.1145/2317956.2317997.

[11] K. N. Dew and D. K. Rosner. “Lessons from the woodshop: Cultivating design with

living materials". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 2018, pp. 1–12.

[12] S. Kuznetsov, C. Barrett, P. Fernando, and K. Fowler. "Antibiotic-responsive bioart: Exploring DIYbio as a design studio practice". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 2018, pp. 1–14.

[13] J. Weiler, P. Fernando, N. Siyambalapitiya, and S. Kuznetsov. "Mycelium artifacts: Exploring shapeable and accessible biofabrication". In: *DIS 2019 Companion - Companion Publication of the 2019 ACM Designing Interactive Systems Conference* (2019), pp. 69–72. DOI: 10.1145/3301019.3325156.

[14] G. Gome, J. Waksberg, A. Grishko, I. Y. Wald, and O. Zuckerman. "OpenLH: Open Liquid-Handling System for Creative Experimentation with Biology". In: *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*. 2019, pp. 55–64.

[15] P. Fernando, M. Pandelakis, and S. Kuznetsov. "Practicing DIYBiology In An HCI Setting". In: *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. CHI EA '16. New York, NY, USA: Association for Computing Machinery, 2016, pp. 2064– 2071. ISBN: 9781450340823. DOI: 10.1145/2851581.2892325. URL: https: //doi.org/10.1145/2851581.2892325.

[16] V. Manzella, C. Gaz, A. Vitaletti, E. Masi, L. Santopolo, S. Mancuso, D. Salazar, and J. De Las Heras. "Plants as sensing devices: the PLEASED experience". In: *Proceedings of the 11th ACM conference on embedded networked sensor systems*. 2013, pp. 1–2.

[17] I. Poupyrev, P. Schoessler, J. Loh, and M. Sato. "Botanicus Interacticus: Interactive Plants Technology". In: *ACM SIGGRAPH 2012 Emerging Technologies*. SIGGRAPH '12. Los Angeles, California: Association for Computing Machinery, 2012. ISBN: 9781450316804. DOI: 10.1145/2343456.2343460. URL: https://doi.org/10.1145/2343456.2343460.

[18] A. D. Cheok, R. T. Kok, C. Tan, O. N. Newton Fernando, T. Merritt, and

J. Y. P. Sen. "Empathetic living media". In: *Proceedings of the 7th ACM conference on Designing interactive systems*. 2008, pp. 465–473.

[19] O. N. N. Fernando, A. D. Cheok, T. Merritt, et al. "Babbage Cabbage: Empathetic Biological Media". In: *Proceedings of the Virtual Reality International Conference: Laval Virtual* (VRIC'09). 2009, pp. 20–23.

[20] S. Kuribayashi, Y. Sakamoto, and H. Tanaka. "I/O plant: a tool kit for designing augmented human-plant interactions". In: *CHI'07 extended abstracts on Human factors in computing systems*. 2007, pp. 2537–2542.

[21] D. Holstius, J. Kembel, A. Hurst, P.-H. Wan, and J. Forlizzi. "Infotropism: living and robotic plants as interactive displays". In: *Proceedings of the 5th conference on Designing interactive systems: processes, practices, methods, and techniques*. 2004, pp. 215–221.

[22] S. Kuribayashi and A. Wakita. "PlantDisplay: turning houseplants into ambient display". In: *Proceedings of the 2006 ACM SIGCHI International Conference on Advances in*

Computer Entertainment Technology. ACE '06. Hollywood, California, USA: Association for Computing Machinery, 2006, 40–es. ISBN: 1595933808. DOI: 10.1145/1178823.1178871. URL: https://doi.org/10.1145/1178823.1178871.

[23] J. H. Seo, A. Sungkajun, and J. Suh. "Touchology: Towards interactive plant design for children with autism and older adults in senior housing". In: *Conference on Human Factors in Computing Systems - Proceedings*. 2015. ISBN: 9781450331463. DOI: 10.1145/2702613.2732883.

[24] B. Barati, E. Karana, S. Pont, and T. van Dortmont. "Living Light Interfaces —An Exploration of Bioluminescence Aesthetics". In: *Designing Interactive Systems Conference 2021*. DIS '21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 1215–1229. ISBN: 9781450384766. DOI: 10.1145/3461778.3462038. URL: https://doi.org/10.1145/3461778.3462038.

[25] E. G. Groutars, C. C. Risseeuw, C. Ingham, R. Hamidjaja, W. S. Elkhuizen, S. C. Pont, and E. Karana. "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*. CHI '22. New Orleans, LA, USA: Association for Computing Machinery, 2022. ISBN: 9781450391573. DOI: 10.1145/3491102.3517713. URL: https: //doi.org/10.1145/3491102.3517713.

[26] P. Pataranutaporn, A. Vujic, D. S. Kong, P. Maes, and M. Sra. "Living Bits: Opportunities and Challenges for Integrating Living Microorganisms in Human-Computer Interaction". In: *Proceedings of the Augmented Humans International Conference*. AHs '20. Kaiserslautern, Germany: Association for Computing Machinery, 2020. ISBN: 9781450376037. DOI: 10.1145/3384657. 3384783. URL: https://doi.org/10.1145/3384657.3384783.

[27] A. D. Ginsberg, J. Calvert, P. Schyfter, A. Elfick, and D. Endy. *Synthetic aesthetics: investigating synthetic biology's designs on nature*. MIT press, 2014.

[28] W. Myers. *Bio design*. Museum of Modern Art, 2012.

[29] J. Fang. Microbial Marketing: bacteria and fungi infect Contagion's billboard. Sept. 2011. URL: https://www.zdnet.com/article/microbial-marketing- bacteria-and-fungi-infect-contagions-billboard/.

[30] L. Evers. Dreaming of a microbial perfume. 2015. URL: https://waag.org/ en/article/dreaming-microbial-perfume.

[31] I. Henriques. Caravel - environmental robot. 2016. URL: https:// www.zdnet.com/article/microbial-marketing-bacteria-and-fungi- infect-contagions-billboard/.

[32] A. Liu. Biota Beats. 2016. URL: http://biotabeats.org/.

[33] H. Fujii, K. Yoshida, and K. Sugimura. Research and development strategy in biological technologies: A patent data analysis of Japanese manufacturing firms. In: *Sustainability*, 8 (4), no. 351. 2016.

[34] V. Mironov, T. Trusk, V. Kasyanov, S. Little, R. Swaja, and R. Markwald. "Biofabrication: a 21st century manufacturing paradigm". In: *Biofabrication* 1.2 (2009), p. 022001.

[35] M. J. Pavlovich, J. Hunsberger, and A. Atala. “Biofabrication: a secret weapon to advance manufacturing, economies, and healthcare”. In: *Trends in biotechnology* 34.9 (2016), pp. 679–680.

[36] MYCOWORKS. URL: https://www.mycoworks.com/.

[37] Living Cocoon. URL: https://loop-biotech.com/nl/living-cocoon/.

[38] S. Balasubramanian, K. Yu, A. S. Meyer, E. Karana, and M.-E. Aubin-Tam. “Bioprinting of regenerative photosynthetic living materials”. In: *Advanced Functional Materials* 31.31 (2021), p. 2011162.

[39] S. Camere and E. Karana. “Fabricating materials from living organisms: An emerging design practice”. In: *Journal of Cleaner Production* 186 (2018), pp. 570–584.

[40] J. Collins. “Synthetic Biology: Bits and pieces come to life”. In: *Nature* 483.7387 (2012), S8–S10.

[41] A. Moisy and L. Pschetz. “Designing with Living Organisms”. In: *Proceedings of the 3rd Biennial Research through Design Conference*. 2017, pp. 323–339.

[42] S. Camere and E. Karana. “Growing materials for product design”. In: *Alive. Active. Adaptive: International Conference on Experiential Knowledge and Emerging Materials*, EKSIG 2017. 2017, pp. 101–115. ISBN: 9788790775902.

[43] V. Ciuffi. “Growing Design”. In: *Abitare Magazine* (531), 2013, pp. 108–111.

[44] M. Montalti. The Growing Lab / Mycelia. 2010. URL: https://www. corpuscoli.com/projects/the-growing-lab/.

[45] C. Bader, W. G. Patrick, D. Kolb, S. G. Hays, S. Keating, S. Sharma, D. Dikovsky,

B. Belocon, J. C. Weaver, P. A. Silver, and N. Oxman. “Grown, printed, and biologically augmented: An additively manufactured microfluidic wearable, functionally templated for synthetic microbes”. In: *3D Printing and Additive Manufacturing* (2016). ISSN: 23297670. DOI: 10.1089/3dp.2016.0027.

[46] R. S. H. Smith, C. Bader, S. Sharma, D. Kolb, T.-C. Tang, A. Hosny, F. Moser,

J. C. Weaver, C. A. Voigt, and N. Oxman. “Hybrid Living Materials: Digital Design and Fabrication of 3D Multimaterial Structures with Programmable Biohybrid Surfaces”. In: *Advanced Functional Materials* 30.7 (2020), p. 1907401.

[47] J. Zhou, B. Barati, J. Wu, D. Scherer, and E. Karana. “Digital biofabrication to realize the potentials of plant roots for product design”. In: *Bio-Design and Manufacturing* (2020). ISSN: 2522-8552. DOI: 10.1007/s42242-020-00088-2. URL: https://doi.org/10.1007/s42242-020-00088-2.

[48] M. Fairs. Mycelium Chair by Eric Klarenbeek is 3D-printed with living fungus. Dezeen. 2013. URL: https://www.dezeen.com/2013/10/20/mycelium-chair-by-eric-klarenbeek-is-3d-printed-with-living-fungus/.

[49] N. Oxman, J. Laucks, M. Kayser, J. Duro-Royo, and C. Gonzales-Uribe. “Silk pavil-

ion: a case study in fiber-based digital fabrication”. In: *FABRICATE Conference Proceedings*. ta Verla. 2014, pp. 248–255.

[50] A. D. Ginsberg and N. Chieza. “Other Biological Futures”. In: *Journal of Design and Science* (2018).

[51] E. Karana, B. Barati, and E. Giaccardi. “Living Artefacts: Conceptualizing Livingness as a Material Quality in Everyday Artefacts.” In: *International Journal of Design* 14.3 (2020), pp. 37–53. URL: http://www.ijdesign.org/ index.php/IJDesign/article/view/3957/923.

[52] J. Liu, D. Byrne, and L. Devendorf. “Design for collaborative survival: An inquiry into human-fungi relationships”. In: *Conference on Human Factors in Computing Systems* - Proceedings 2018-April (2018). DOI: 10.1145/3173574.3173614.

[53] N. Smith, S. Bardzell, and J. Bardzell. “Designing for Cohabitation: Naturecultures, Hybrids, and Decentering the Human in Design”. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI ’17. Denver, Colorado, USA: Association for Computing Machinery, 2017, pp. 1714–1725. ISBN: 9781450346559. DOI: 10.1145/ 3025453.3025948. URL: https://doi.org/10.1145/3025453.3025948.

[54] R. Clarke, S. Heitlinger, A. Light, L. Forlano, M. Foth, and C. DiSalvo. “More-than-human participation: design for sustainable smart city futures”. In: *Interactions* 26.3 (2019), pp. 60–63.

[55] L. Forlano. “Decentering the human in the design of collaborative cities”. In:

Design Issues 32.3 (2016). DOI: 10.1162/DESI. URL: www.magno-design.com.

[56] C. Mancini. “Animal-computer interaction (ACI) changing perspective on HCI, participation and sustainability”. In: *CHI’13 Extended Abstracts on Human Factors in Computing Systems*. 2013, pp. 2227–2236.

[57] R. E. McGrath. “Species-Appropriate Computer Mediated Interaction”. In: *CHI ’09 Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’09. Boston, MA, USA: Association for Computing Machinery, 2009, pp. 2529–2534. ISBN: 9781605582474. DOI: 10.1145/1520340.1520357. URL: https://doi.org/10.1145/1520340.1520357.

[58] E. Nyberg, A. M. Hipkiss, and D. Sanders. “Plants to the fore: Noticing plants in designed environments”. In: *Plants, People, Planet* 1.3 (2019), pp. 212–220.

[59] P. Flanagan and R. Frankjær. “Cyborganic wearables: Sociotechnical misbe- havior and the evolution of nonhuman agency”. In: *Reconfiguring human, nonhuman and posthuman in literature and culture*. Routledge, 2019, pp. 236–259.

[60] F. Aspling, J. Wang, and O. Juhlin. “Plant-computer interaction, beauty and dissemination”. In: *Proceedings of the Third International Conference on Animal-Computer Interaction*. 2016, pp. 1–10.

[61] A. L. Tsing. *The mushroom at the end of the world: On the possibility of life in capitalist ruins*. Princeton University Press, 2015.

[62] D. Chen, Y. a. Seong, H. Ogura, Y. Mitani, N. Sekiya, and K. Moriya. “Nukabot: Design

of Care for Human-Microbe Relationships". 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: 10.1145/3411763.3451605. URL: https: //doi.org/10.1145/3411763.3451605.

[63] S. Bardzell and J. Bardzell. "Towards a feminist HCI methodology: social science, feminism, and HCI". In: *Proceedings of the SIGCHI conference on human factors in computing systems*. 2011, pp. 675–684.

[64] R. Comber, S. Bardzell, J. Bardzell, M. Hazas, and M. Muller. "Announcing a New CHI Subcommittee: Critical and Sustainable Computing". In: *Interactions* 27.4 (July 2020), pp. 101–103. ISSN: 1072-5520. DOI: 10.1145/3407228. URL: https://doi.org/10.1145/3407228.

[65] A. Light, A. Powell, and I. Shklovski. "Design for existential crisis in the anthropocene age". In: *Proceedings of the 8th International Conference on Communities and Technologies*. 2017, pp. 270–279.

[66] S.-Y. Liu, S. Bardzell, and J. Bardzell. "Symbiotic Encounters: HCI and Sustainable Agriculture". 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/ 3290605.3300547. URL: https://doi.org/10.1145/3290605.3300547.

[67] P. Jurtshuk. "Bacterial metabolism". In: *Medical Microbiology* 4 (1996).

[68] D. Voet and J. G. Voet. Bioquímica. Ed. *Médica Panamericana*, 2006.

[69] M. Westerlaken. *Imagining multispecies worlds*. Malmö University, 2020.

[70] S. F. Gilbert, J. Sapp, and A. I. Tauber. "A symbiotic view of life: we have never been individuals". In: *The Quarterly review of biology* 87.4 (2012), pp. 325–341.

[71] S. Martini and S. H. Haddock. "Quantification of bioluminescence from the surface to the deep sea demonstrates its predominance as an ecological trait". In: *Scientific reports* 7.1 (2017), p. 45750.

[72] C. Ramirez-Figueroa, L. Hernan, and L. Pei-Ying. "The biological unseen. Producing and mediating imaginaries of protocells". In: *Proceedings of the 5th Biennial Transdisciplinary Imaging Conference 2018*. Transdisciplinary image Conference. 2018, pp. 122–137.

[73] H. S. Lin and J. C. Wooley. *Catalyzing inquiry at the interface of computing and biology*. National Academies Press, 2006.

[74] G. W. Brodland. "How computational models can help unlock biological systems". In: *Seminars in cell & developmental biology*. Vol. 47. Elsevier. 2015, pp. 62–73.

[75] C. Bader, S. Sharma, R. S. H. Smith, J. Disset, and N. Oxman. "Viva in silico: A position-based dynamics model for microcolony morphology simulation". In: *ALIFE 2018 - 2018 Conference on Artificial Life: Beyond AI* (2018), pp. 304–310. DOI: 10.1162/isal_a_00060.

[76] C. M. Macal and M. J. North. "Tutorial on agent-based modeling and simulation". In: *Proceedings of the Winter Simulation Conference*, 2005. IEEE. 2005, 14–pp.

[77] N. Oxman. “Material-based design computation”. PhD thesis. Massachusetts Institute of Technology, 2010.

[78] B. V. D. Nguyen, T.-H. Wang, and C. Peng. “Integration of agent- based modelling of social-spatial processes in architectural parametric design”. In: *Architectural Science Review* 63.2 (2020), pp. 119–134. DOI: 10.1080/00038628.2019.1640107. URL: https://doi.org/10.1080/00038628.2019.1640107.

[79] G. N. Bancroft, V. I. Sikavitsas, J. van den Dolder, T. L. Sheffield, C. G. Ambrose, J. A. Jansen, and A. G. Mikos. “Fluid flow increases mineralized matrix deposition in 3D perfusion culture of marrow stromal osteoblasts in a dose-dependent manner”. In: *Proceedings of the National Academy of Sciences* 99.20 (2002), pp. 12600–12605.

[80] C. Pasquero and M. Poletto. “Bio-digital aesthetics as value system of post-Anthropocene architecture”. In: *International Journal of Architectural Computing* 18.2 (2020), pp. 120–140. DOI: 10.1177/1478077120922941. URL: https://doi.org/10.1177/1478077120922941.

[81] Z. Liu, M. Tamaddon, Y. Gu, J. Yu, N. Xu, F. Gang, X. Sun, and C. Liu. “Cell Seeding Process Experiment and Simulation on Three- Dimensional Polyhedron and Cross-Link Design Scaffolds”. In: *Frontiers in Bioengineering and Biotechnology* 8 (2020), p. 104. ISSN: 2296-4185. DOI: 10.3389/fbioe.2020.00104. URL: https://www.frontiersin.org/article/10.3389/fbioe.2020.00104.

[82] H. Jian, M. Wang, S. Wang, A. Wang, and S. Bai. “3D bioprinting for cell culture and tissue fabrication”. In: *Bio-Design and Manufacturing* 1.1 (2018), pp. 45–61. ISSN: 2522-8552. DOI: 10.1007/s42242-018-0006-1. URL: https://doi.org/10.1007/s42242-018-0006-1.

[83] X. Liu, H. Yuk, S. Lin, G. A. Parada, T. C. Tang, E. Tham, C. de la Fuente- Nunez, T. K. Lu, and X. Zhao. “3D Printing of Living Responsive Materials and Devices”. In: *Advanced Materials* 30.4 (2017). ISSN: 15214095. DOI: 10.1002/adma.201704821.

[84] Q. Huang, F. Jiang, L. Wang, and C. Yang. “Design of photobioreactors for mass cultivation of photosynthetic organisms”. In: *Engineering* 3.3 (2017), pp. 318–329.

[85] D. Briscoe. “Living Wall: Digital Design and Implementation”. In: *Journal of Digital Landscape Architecture* (2020), pp. 646–653.

[86] R. A. Timmers, D. P. Strik, H. V. Hamelers, and C. J. Buisman. “Long-term performance of a plant microbial fuel cell with Spartina anglica”. In: *Applied microbiology and biotechnology* 86.3 (2010), pp. 973–981.

[87] J. Fromm and S. Lautner. “Electrical signals and their physiological significance in plants”. In: *Plant, cell & environment* 30.3 (2007), pp. 249–257.

[88] D. Correa, S. Poppinga, M. D. Mylo, A. S. Westermeier, B. Bruchmann, A. Menges, and T. Speck. “4D pine scale: biomimetic 4D printed autonomous scale and flap structures capable of multi-phase movement”. In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 378.2167 (2020), p. 20190445. DOI: 10.1098/rsta.2019.0445. eprint: https://royalsocietypublishing.org/doi/pdf/10.1098/

rsta.2019. 0445. URL: https://royalsocietypublishing.org/doi/abs/10.1098/ rsta.2019.0445.

[89] J. Forman, T. Tabb, Y. Do, M.-H. Yeh, A. Galvin, and L. Yao. "ModiFiber: Two-Way Morphing Soft Thread Actuators for Tangible Interaction". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–11. ISBN: 9781450359702. DOI: 10.1145/3290605.3300890. URL: https://doi.org/10.1145/3290605.3300890.

[90] Y. Liu, J. K. Boyles, J. Genzer, and M. D. Dickey. "Self-folding of polymer sheets using local light absorption". In: *Soft Matter* 8 (2012), pp. 1764–1769. URL: https://api.semanticscholar.org/CorpusID:37627587.

[91] N. Umetani, A. Panotopoulou, R. Schmidt, and E. Whiting. "Printone: interactive resonance simulation for free-form print-wind instrument design". In: *ACM Trans. Graph.* 35.6 (Dec. 2016). ISSN: 0730-0301. DOI: 10.1145/ 2980179.2980250. URL: https://doi.org/10.1145/2980179.2980250.

[92] J. Ou, Z. Ma, J. Peters, S. Dai, N. Vlavianos, and H. Ishii. "KinetiX - designing auxetic-inspired deformable material structures". In: *Comput. Graph.* 75.C (Oct. 2018), pp. 72–81. ISSN: 0097-8493. DOI: 10.1016/j.cag.2018.06.003. URL: https://doi.org/10.1016/j.cag.2018.06.003.

[93] M. Wehner, R. L. Truby, D. J. Fitzgerald, B. Mosadegh, G. M. Whitesides, J. A. Lewis, and R. J. Wood. "An integrated design and fabrication strategy for entirely soft, autonomous robots". In: *nature* 536.7617 (2016), pp. 451–455.

[94] W. Jensen, M. Löchtefeld, and H. Knoche. "ShadowLamp: An Ambient Display with Controllable Shadow Projection Using Electrochromic Materials." In: *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI EA '19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–6. ISBN: 9781450359719. DOI: 10.1145/ 3290607.3313011. URL: https://doi.org/10.1145/3290607.3313011.

[95] V. Kapsali and J. Vincent. "From a Pinecone to Design of an Active Textile". In: *Biomimetics* 5.4 (2020). ISSN: 2313-7673. DOI: 10.3390/biomimetics5040052. URL: https://www.mdpi.com/2313-7673/5/4/52.

[96] D. Vyas, W. Poelman, A. Nijholt, and A. De Bruijn. "Smart material interfaces: a new form of physical interaction". In: *CHI '12 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '12. Austin, Texas, USA: Association for Computing Machinery, 2012, pp. 1721–1726. ISBN: 9781450310161. DOI: 10 .1145 /2212776 .2223699. URL: https: //doi.org/10.1145/2212776.2223699.

[97] G. Wang, L. Yao, W. Wang, J. Ou, C.-Y. Cheng, and H. Ishii. "xPrint: A Modularized Liquid Printer for Smart Materials Deposition". 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. 5743–5752. ISBN: 9781450333627. DOI: 10.1145/2858036.2858281. URL: https://doi.org/10.1145/2858036.2858281.

[98] J. Ou, G. Dublon, C.-Y. Cheng, F. Heibeck, K. Willis, and H. Ishii. "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. CHI ’16. San Jose, California, USA: Association for Computing Machinery, 2016, pp. 5753–5764. ISBN: 9781450333627. DOI: 10.1145/ 2858036.2858257. URL: https://doi.org/10.1145/2858036.2858257.

[99] J. Ou, M. Skouras, N. Vlavianos, F. Heibeck, C.-Y. Cheng, J. Peters, and H. Ishii. “aeroMorph - Heat-sealing Inflatable Shape-change Materials for Interaction Design”. In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST ’16. Tokyo, Japan: Association for Computing Machinery, 2016, pp. 121–132. ISBN: 9781450341899. DOI: 10.1145/2984511. 2984520. URL: https://doi.org/10.1145/2984511.2984520.

[100] L. Yao, R. Niiyama, J. Ou, S. Follmer, C. Della Silva, and H. Ishii. “PneUI: pneumatically actuated soft composite materials for shape changing interfaces”. In: *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*. UIST ’13. St. Andrews, Scotland, United Kingdom: Association for Computing Machinery, 2013, pp. 13–22. ISBN: 9781450322683. DOI: 10.1145/2501988.2502037. URL: https: //doi. org/10.1145/2501988.2502037.

[101] K. Vidimce, A. Kaspar, Y. Wang, and W. Matusik. “Foundry: Hierarchical Material Design for Multi-Material Fabrication”. In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST ’16. Tokyo, Japan: Association for Computing Machinery, 2016, pp. 563–574. ISBN: 9781450341899. DOI: 10.1145/2984511.2984516. URL: https://doi.org/10.1145/2984511.2984516.

[102] S. Tibbits. “4D Printing: Multi-Material Shape Change”. In: *Architectural Design* 84.1 (2014), pp. 116–121. DOI: https://doi.org/10.1002/ad.1710. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/ad.1710. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/ ad.1710.

[103] A. Ion, J. Frohnhofen, L. Wall, R. Kovacs, M. Alistar, J. Lindsay, P. Lopes, H.-T. Chen, and P. Baudisch. “Metamaterial Mechanisms”. In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST ’16. Tokyo, Japan: Association for Computing Machinery, 2016, pp. 529–539. ISBN: 9781450341899. DOI: 10.1145/2984511.2984540. URL: https://doi.org/10.1145/2984511.2984540.

[104] M. Barozzi, J. Lienhard, A. Zanelli, and C. Monticelli. “The Sustainability of Adaptive Envelopes: Developments of Kinetic Architecture”. In: *Procedia Engineering 155 (2016). TENSINET – COST TU1303 International Symposium* 2016, pp. 275–284. ISSN: 1877-7058. DOI: https://doi.org/10.1016/j.proeng.2016.08.029. URL: https: //www.sciencedirect. com/science/article/pii/S1877705816321701.

[105] M. Miodownik, R. Morris, et al. *Animate Materials*. Tech. rep. The Royal Society, 2021.

[106] L. M. González, N. Mukhitov, and C. A. Voigt. “Resilient living materials built by printing bacterial spores”. In: *Nature chemical biology* 16.2 (2020), pp. 126–133.

[107] P. Sundström, A. Taylor, K. Grufberg, N. Wirström, J. Solsona Belenguer, and M. Lundén. “Inspirational bits: towards a shared understanding of the digital material”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Sys-*

tems. CHI ’11. Vancouver, BC, Canada: Association for Computing Machinery, 2011, pp. 1561–1570. ISBN: 9781450302289. DOI: 10.1145/1978942.1979170. URL: https://doi.org/10.1145/1978942.1979170.

[108] A. Dearden. “Designing as a conversation with digital materials”. In: *Design Studies* 27.3 (2006). Digital Design, pp. 399–421. ISSN: 0142-694X. DOI: https://doi.org/10.1016/j.destud.2005.11.004. URL: https: //www.sciencedirect.com/science/article/pii/S0142694X05000906.

[109] J. Hiller and H. Lipson. “Design and analysis of digital materials for physical 3D voxel printing”. In: *Rapid Prototyping Journal* 15.2 (2009), pp. 137–149.

[110] K. Helms. “Designing with care: Self-centered research for interaction design otherwise”. PhD thesis. KTH Royal Institute of Technology, 2023.

[111] M. L. Lee-Smith, J. J. Benjamin, A. Desjardins, M. Funk, W. Odom, D. Oogjes, Y.-W. Park, J. Pierce, P. Sanches, and V. Tsaknaki. “Data as a Material for Design: Alternative Narratives, Divergent Pathways, and Future Directions”. 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: 10.1145/3544549.3573817. URL: https://doi.org/10.1145/3544549.3573817.

[112] A. Gomez Ortega, J. van Kollenburg, Y. Shen, D. Murray-Rust, D. Nedic, J. C. Jimenez, W. Meijer, P. K. K. Chaudhary, and J. Bourgeois. “SIG on Data as Human-Centered Design Material”. In: *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI EA ’22. New Orleans, LA, USA: Association for Computing Machinery, 2022. ISBN: 9781450391566. DOI: 10.1145/3491101.3516403. URL: https: //doi.org/10.1145/3491101.3516403.

[113] L. E. Holmquist. “Intelligence on tap: artificial intelligence as a new design material”. In: *interactions* 24.4 (2017), pp. 28–33.

[114] H. Ishii and B. Ullmer. “Tangible bits: towards seamless interfaces between people, bits and atoms”. In: *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*. 1997, pp. 234–241.

[115] M. P. de la Bellacasa. *Matters of Care: Speculative Ethics in More than Human Worlds*. Minneapolis: University of Minnesota Press, 2017. ISBN: 9781517900656. URL: http://www.jstor.org/stable/10.5749/j. ctt1mmfspt (visited on 05/17/2023).

[116] E. Karana, B. Barati, V. Rognoli, A. Zeeuw Van Der Laan, et al. “Material driven design (MDD): A method to design for material experiences”. In: *International Journal of Design* 9.2 (2015), pp. 35–54.

[117] E. F. Keller. *A feeling for the organism*, 10th aniversary edition: the life and work of Barbara McClintock. Macmillan, 1984.

[118] S. Parisi, V. Rognoli, and M. Sonneveld. “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. URL:

https://doi.org/10.1080/14606925.2017.1353059.

[119] W. Biggley, E. Swift, R. Buchanan, and H. Seliger. “Stimulable and spontaneous bioluminescence in the marine dinoflagellates, Pyrodinium bahamense, Gonyaulax polyedra, and Pyrocystis lunula”. In: *The Journal of general physiology* 54.1 (1969), p. 96.

[120] E. Swift, W. H. Biggley, and H. H. Seliger. “Species of oceanic dinoflagellates in the genera dissodinium and pyrocystis: interclonal and interspecific comparisons of the color and photon yield of bioluminescence 1”. In: *Journal of Phycology* 9.4 (1973), pp. 420–426.

[121] A. H. Knoll. *Life on a Young Planet: The First Three Billion Years of Evolution on Earth*. Princeton University Press, 2015.

[122] A. Belay, Y. Ota, K. Miyakawa, and H. Shimamatsu. “Current knowledge on potential health benefits of Spirulina”. In: *Journal of applied Phycology* 5 (1993), pp. 235–241.

[123] M. A. B. Habib, M. Parvin, T. C. Huntington, M. R. Hasan, et al. A review on culture, production and use of Spirulina as food for humans and feeds for domestic animals. 2008.

[124] A. Richmond et al. *Handbook of microalgal culture: biotechnology and applied phycology*. Vol. 577. Wiley Online Library, 2004.

[125] C. Parisi, M. Vigani, and E. Rodríguez-Cerezo. “Agricultural Nanotechnologies: What are the current possibilities?” In: *Nano Today* 10.2 (2015), pp. 124–127. ISSN: 1748-0132. DOI: https://doi.org/10.1016/j.nantod.2014.09.009. URL: https://www.sciencedirect.com/science/article/pii/ S1748013214001340.

[126] R. Kim, C. Risseeuw, E. G. Groutars, and E. Karana. “Surfacing Livingness in Microbial Displays: A Design Taxonomy for HCI”. 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 .3581417. URL: https://doi.org/10.1145/3544548.3581417.

[127] D. Easterly, M. Kenyon, and T. Rorke. “Tardigotchi: Considerations on Pets and Digital Simulations”. In: *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’11. Easterly. Funchal, Portugal: Association for Computing Machinery, 2010, pp. 391–392. ISBN: 9781450304788. DOI: 10.1145/1935701.1935795. URL: https://doi.org/10.1145/1935701.1935795.

[128] M. P. de la Bellacasa. “Re-animating soils: Transforming human–soil affections through science, culture and community”. In: *The Sociological Review* 67.2 (2019), pp. 391–407. DOI: 10.1177/0038026119830601.eprint: https://doi.org/10.1177/0038026119830601. URL: https://doi.org/10.1177/0038026119830601.

[129] P. van Allen, J. McVeigh-Schultz, B. Brown, H. M. Kim, and D. Lara. “AniThings: Animism and Heterogeneous Multiplicity”. In: *CHI ’13 Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’13. Paris, France: Association for Computing Machinery, 2013, pp. 2247–2256. ISBN: 9781450319522. DOI: 10 .1145 /2468356 .2468746. URL: https: //doi.org/10.1145/2468356.2468746.

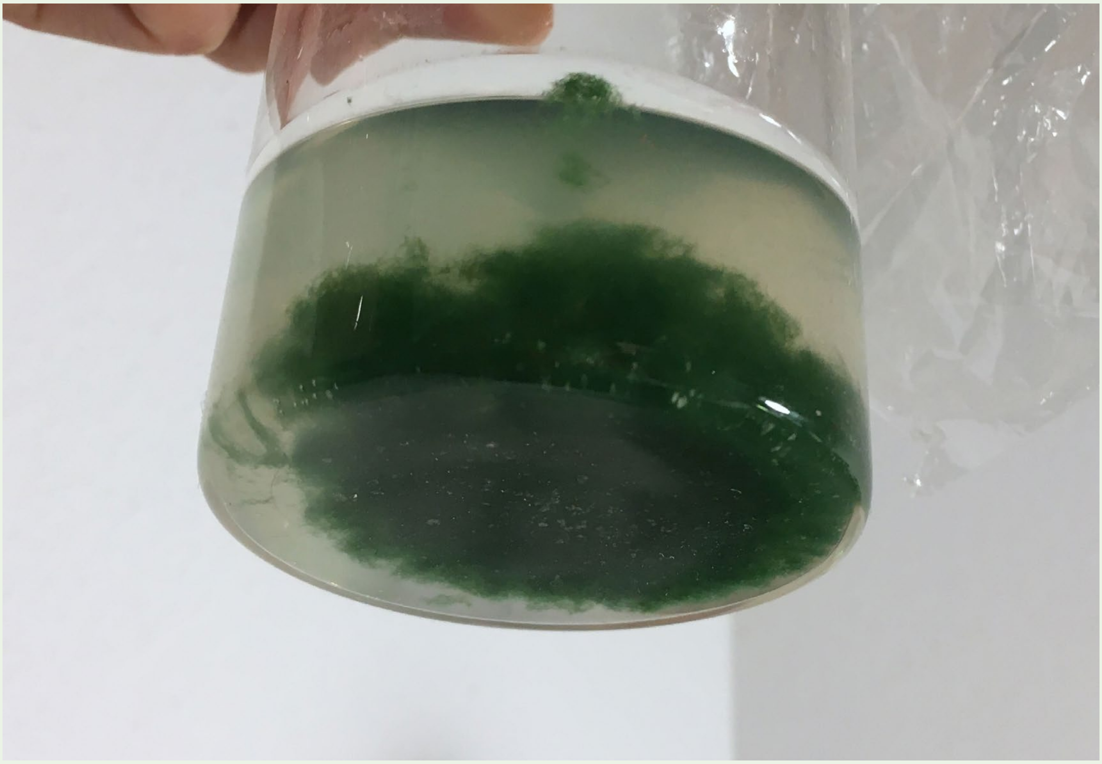
[130] B. Marenko and P. van Allen. “Animistic design: how to reimagine digital interac-

tion between the human and the nonhuman". In: *Digital Creativity* 27.1 (2016), pp. 52–70. DOI: 10.1080/14626268.2016.1145127. eprint: https://doi.org/10.1080/14626268.2016.1145127. URL: https://doi.org/10.1080/14626268.2016.1145127.

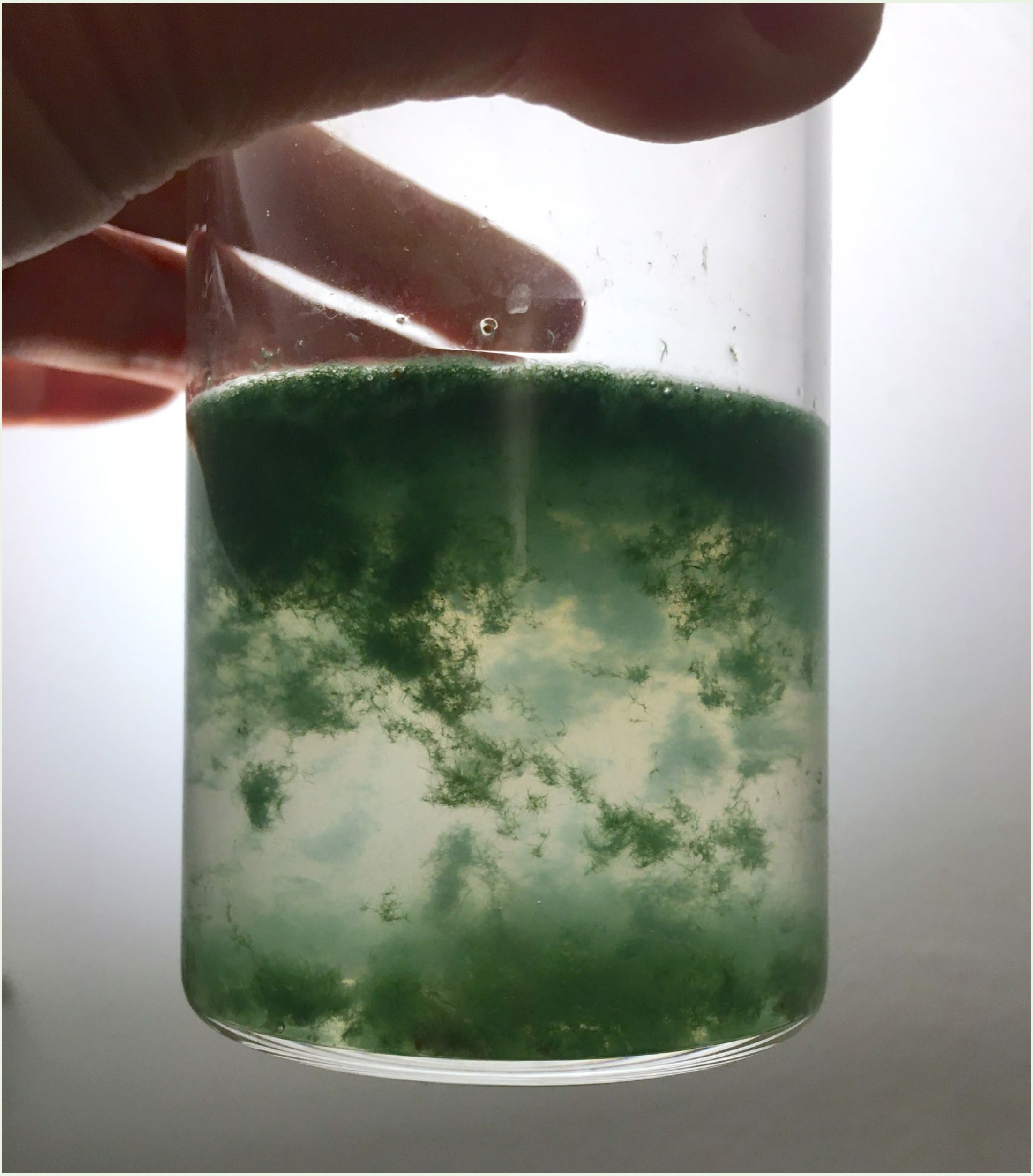
[131] F. Heider and M. Simmel. "An Experimental Study of Apparent Behavior". In: *The American Journal of Psychology* 57.2 (1944), pp. 243–259. ISSN: 00029556. URL: http://www.jstor.org/stable/1416950 (visited on 09/13/2024).

[132] P. Arcari. "'Dynamic' Non-human Animals in Theories of Practice: Views from the Subaltern". In: *Social Practices and Dynamic Non-Humans: Nature, Materials and Technologies*. Ed. by C. Maller and Y. Strengers. Cham: Springer International Publishing, 2019, pp. 63–86. ISBN: 978-3-319-92189-1. DOI: 10.1007/978-3-319-92189-1_4. URL: https://doi.org/10.1007/978-3-319-92189-1_4.

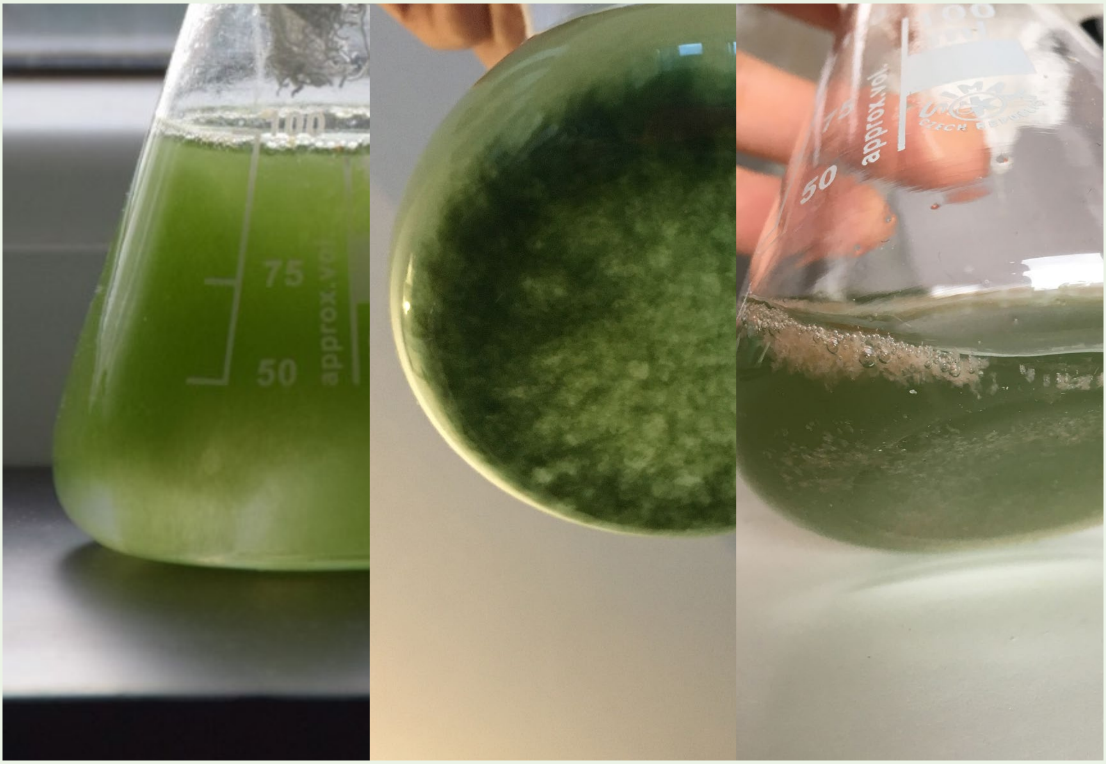
Visual Essay—Living with Cyanobacterium Spirulina platensis



Gently stirring the living broth, dispersing cells in graceful rhythm, a dance to break their crowded embrace, letting each thrive in fluid space.



Fibrous cells sway and suspend,
delicate threads in liquid blend.
Dancing softly in aqueous flow,
a quiet ballet, a rhythmic glow.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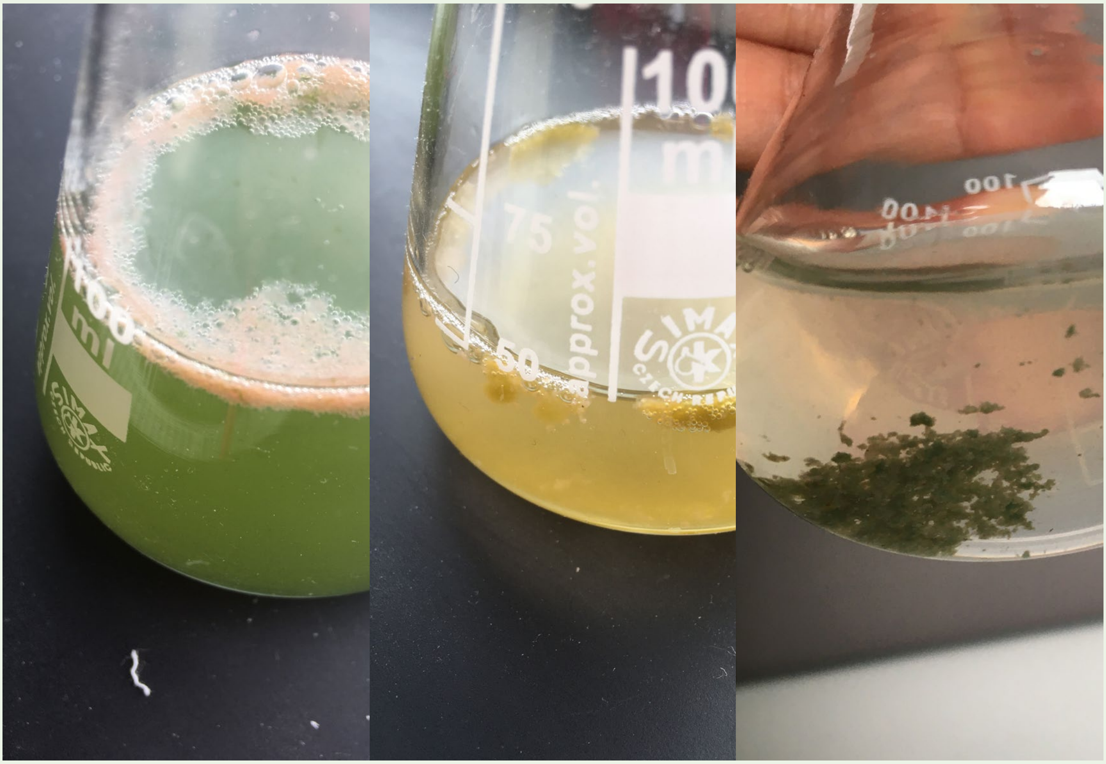
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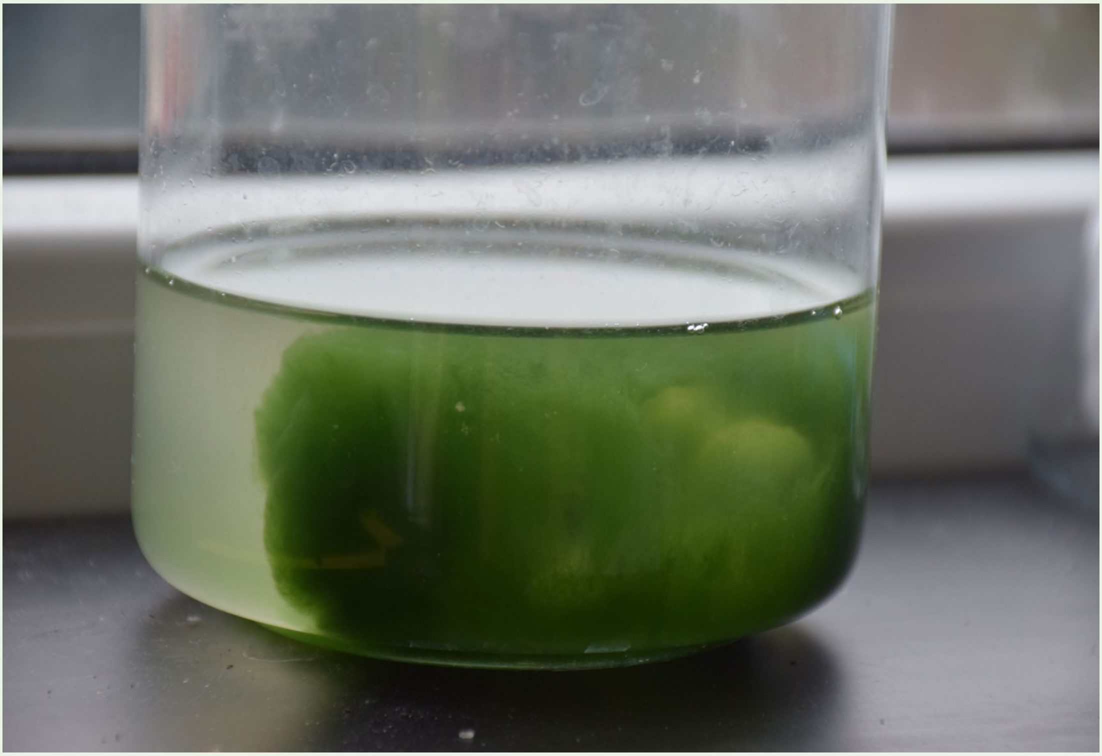
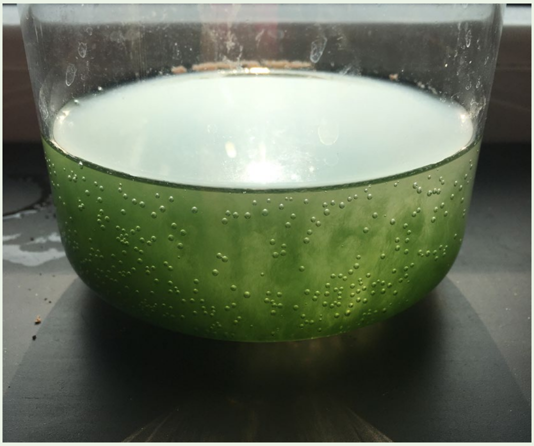
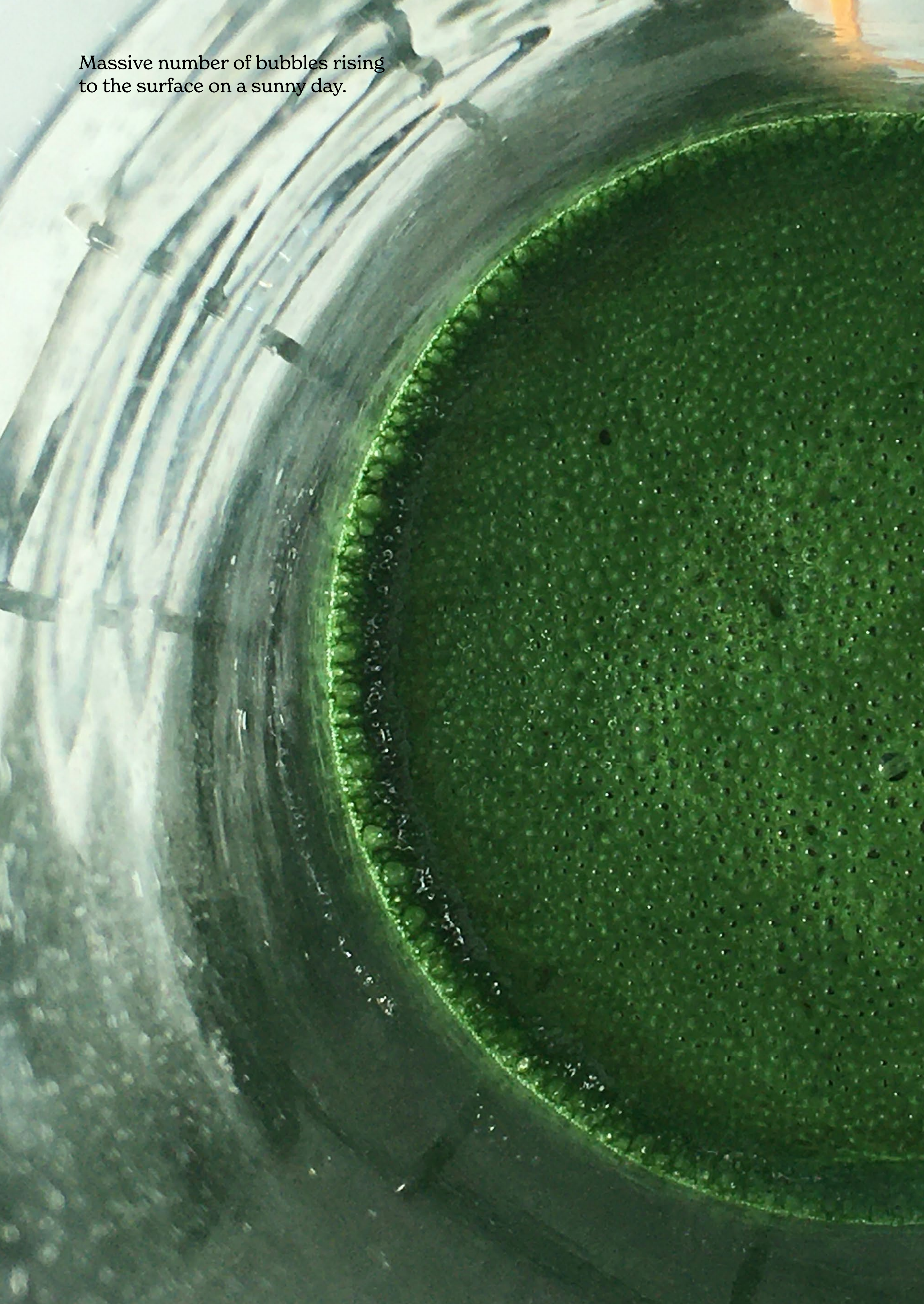
"Mom" and "son"...
A trace of personal touch in the way I labelled the cultures

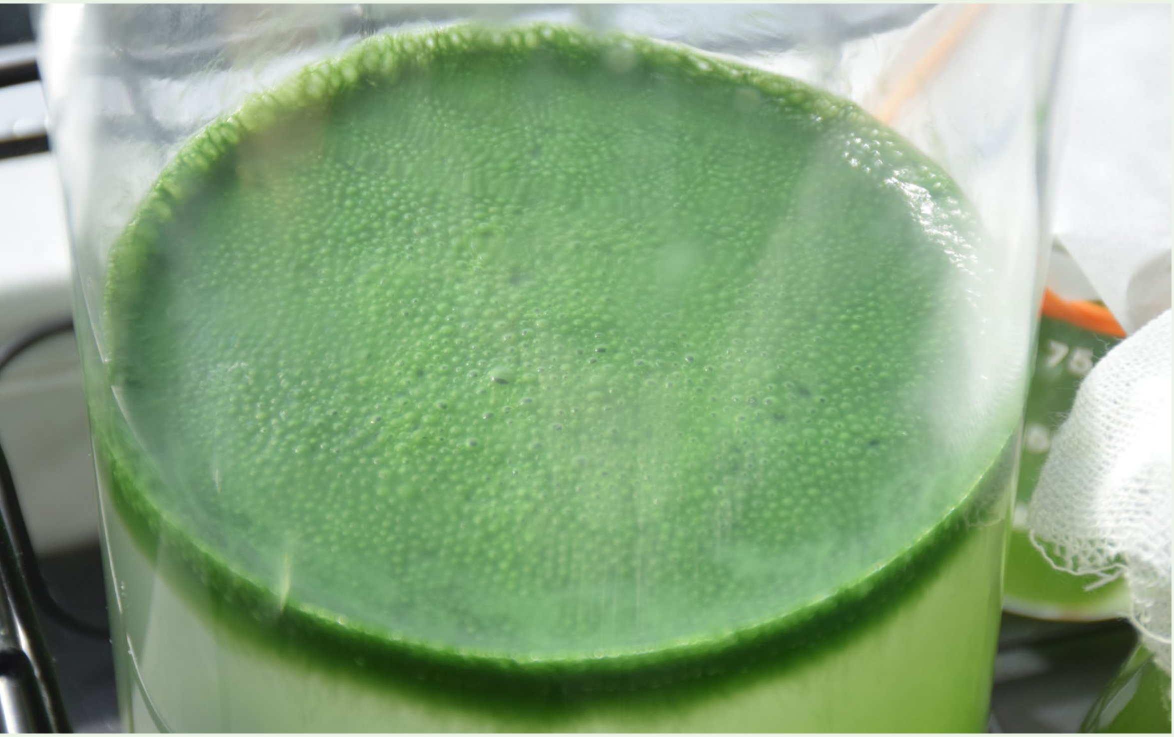


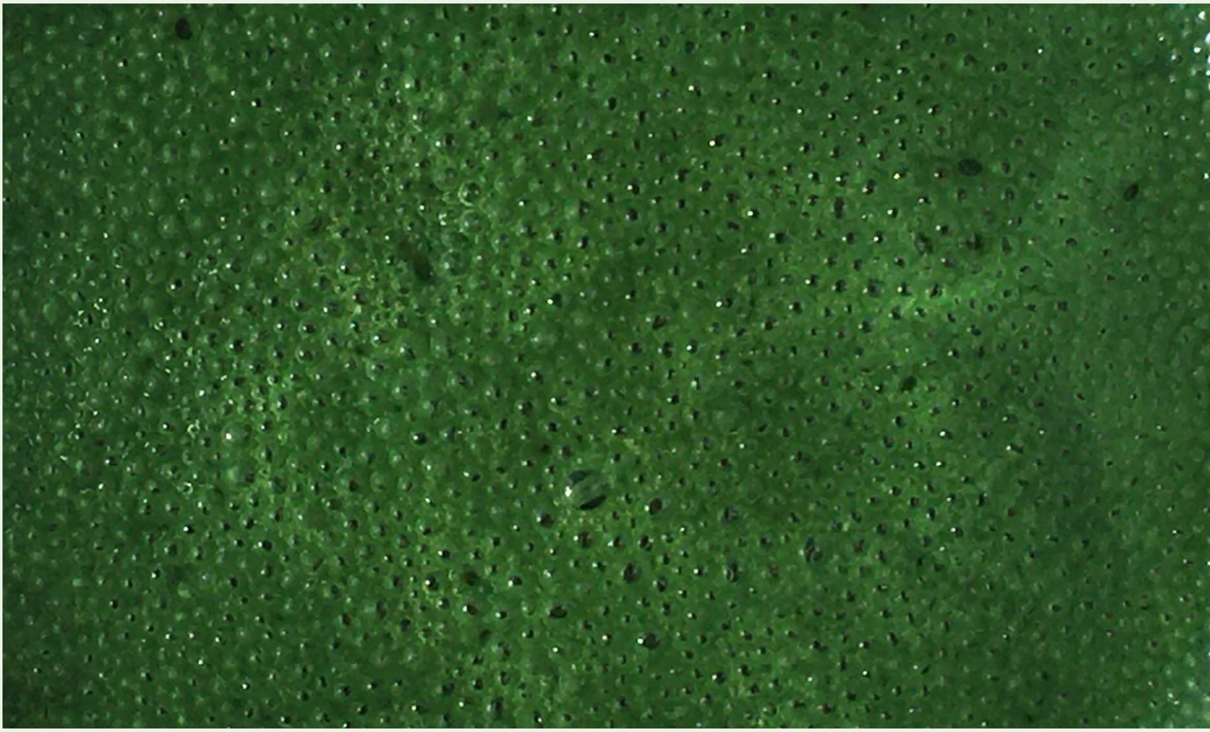
When left unshaken, they gather close,
forming clusters—
a silent choreography of stillness,
seeking comfort in collective embrace.

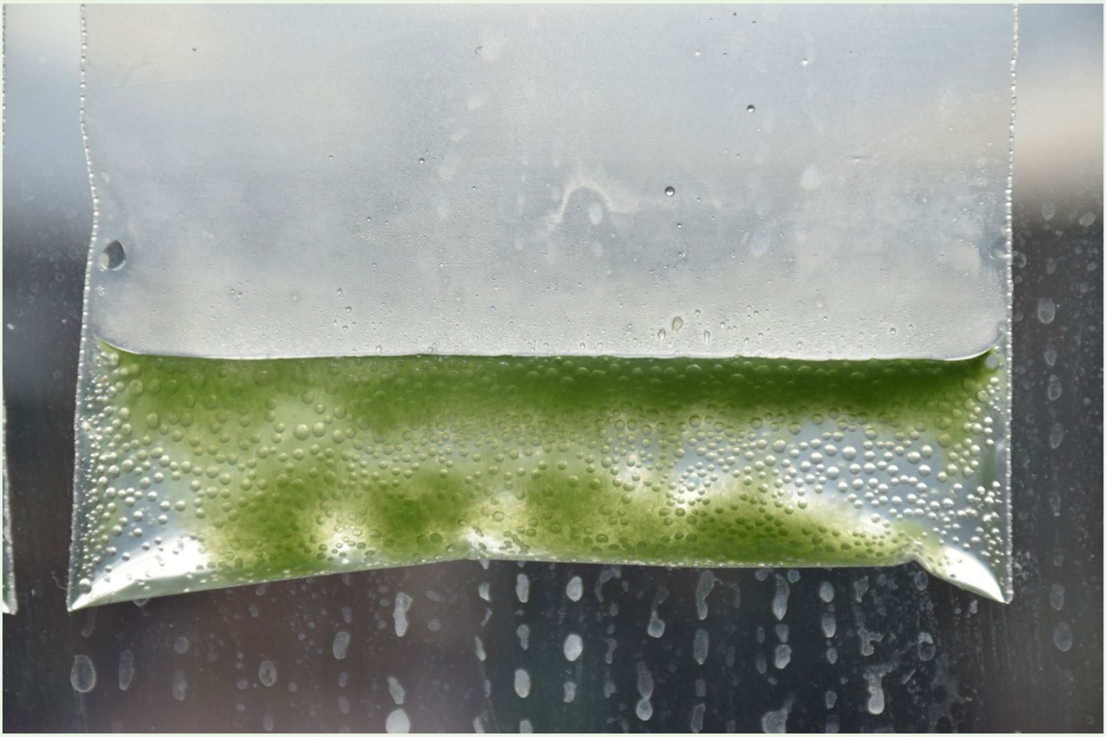


Massive number of bubbles rising
to the surface on a sunny day.







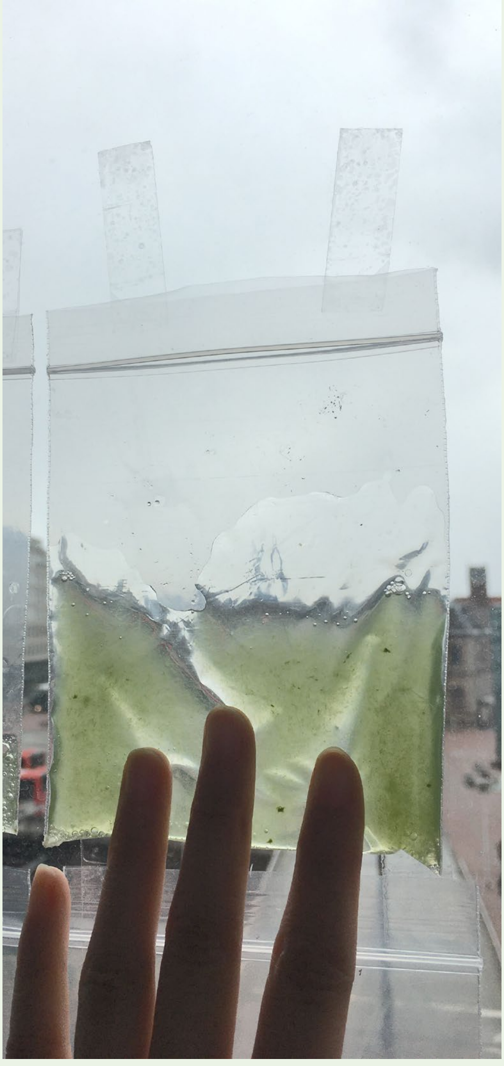


Bubbles rising,
tiny breathmarks of life—
a whispered proof of
photosynthesis,
where light dances with water,
and air is born anew.

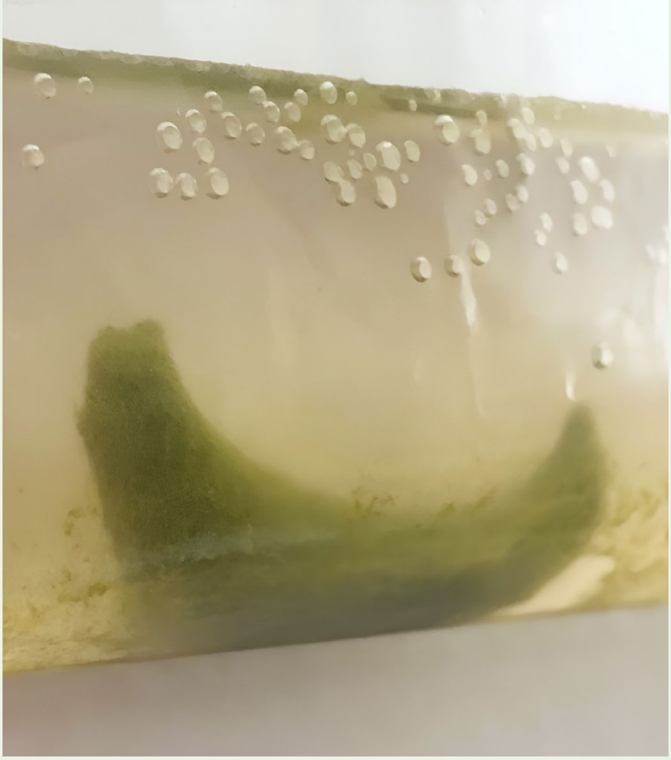
In the alternative habitat, the cyanobacteria slowly assembled into a form reminiscent of a "caterpillar," their delicate structure hinting at life adapting in graceful yet unexpected ways.

Each habitat stands distinct, shaped by its unique interactions and surroundings, yet an underlying rhythm of similarity binds them—a shared essence that weaves through their differences, connecting them in an unseen continuity.

Alternative habitat and care actions...

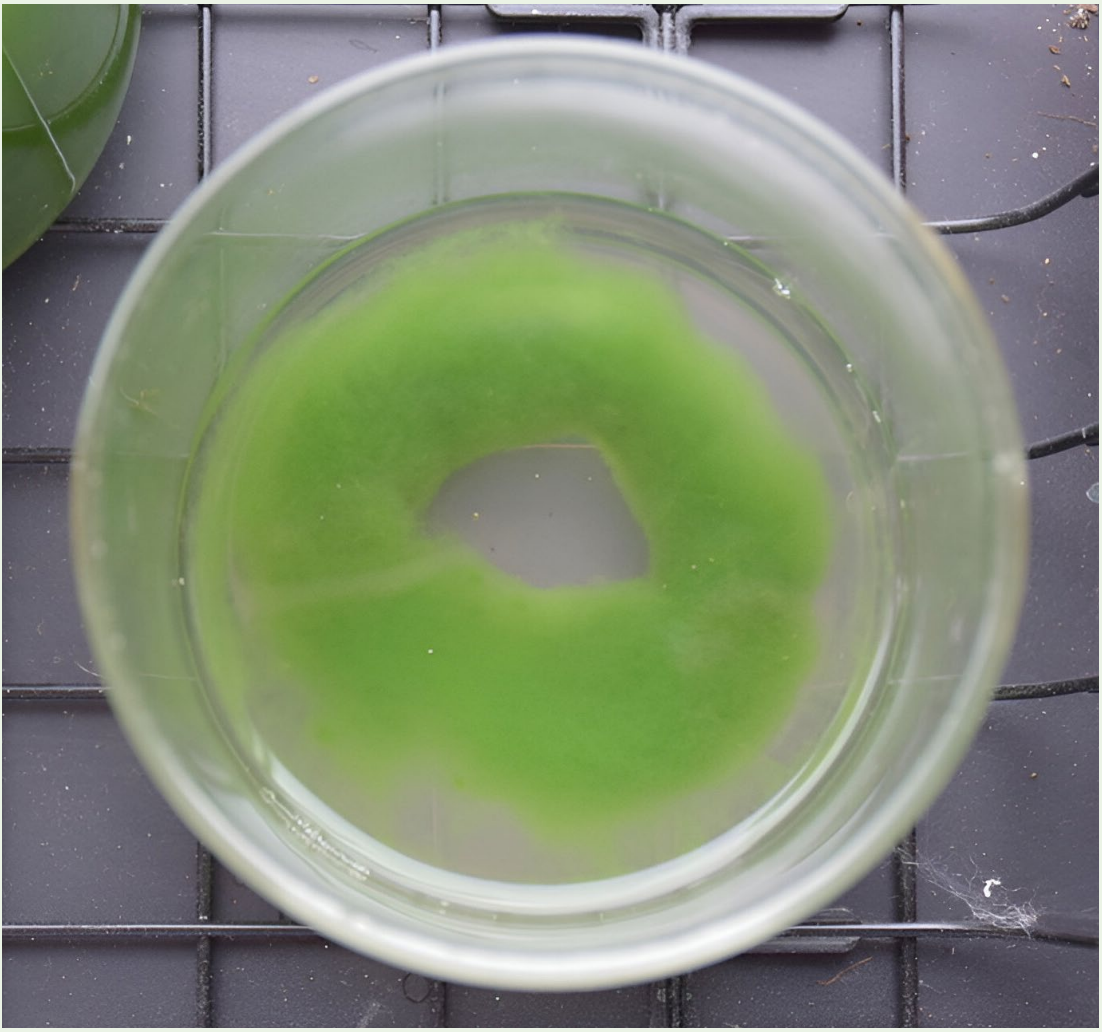


I unzipped the bag, letting air flow in and out, creating a subtle exchange between the inside and outside worlds. A light tap on the bag stirred the culture within, gently awakening it and disrupting the stillness to maintain balance and vitality.



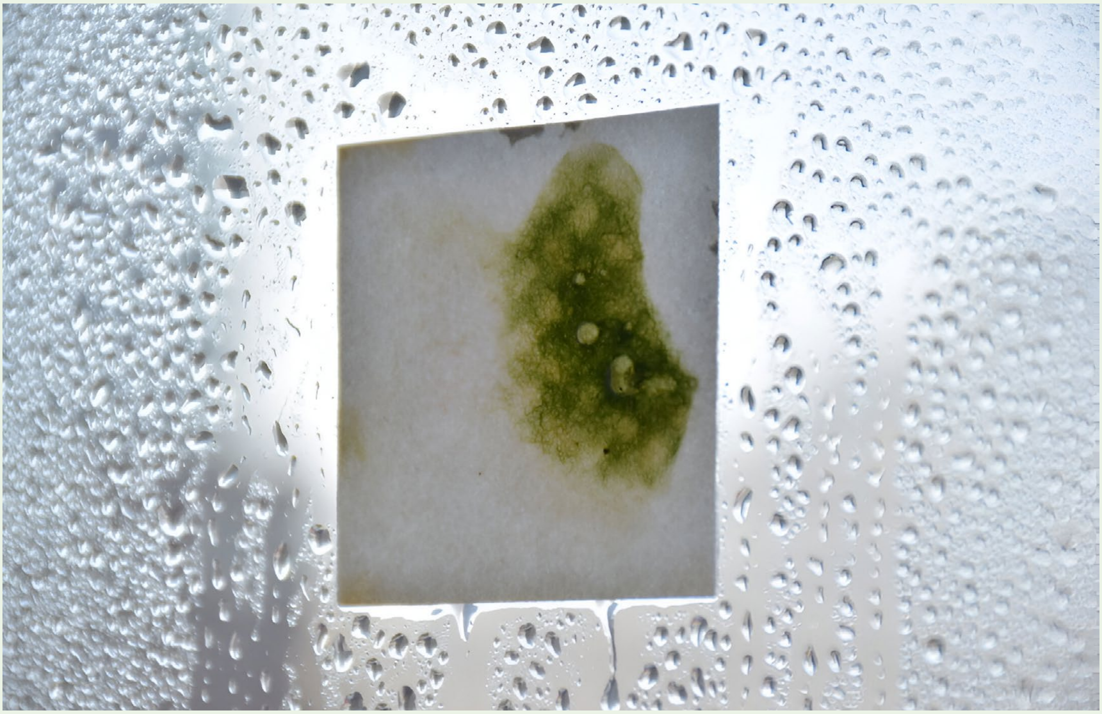
The cultures, in their unique habitats, simultaneously shaped themselves into two delicate "crescents," mirroring each other like reflections caught in distinct yet parallel worlds.

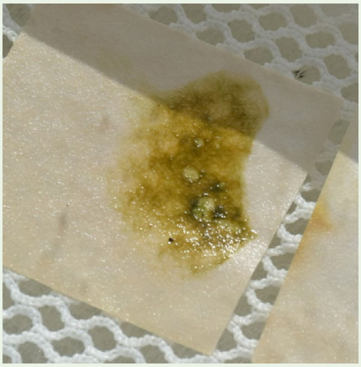
A message from Spirulina platensis?

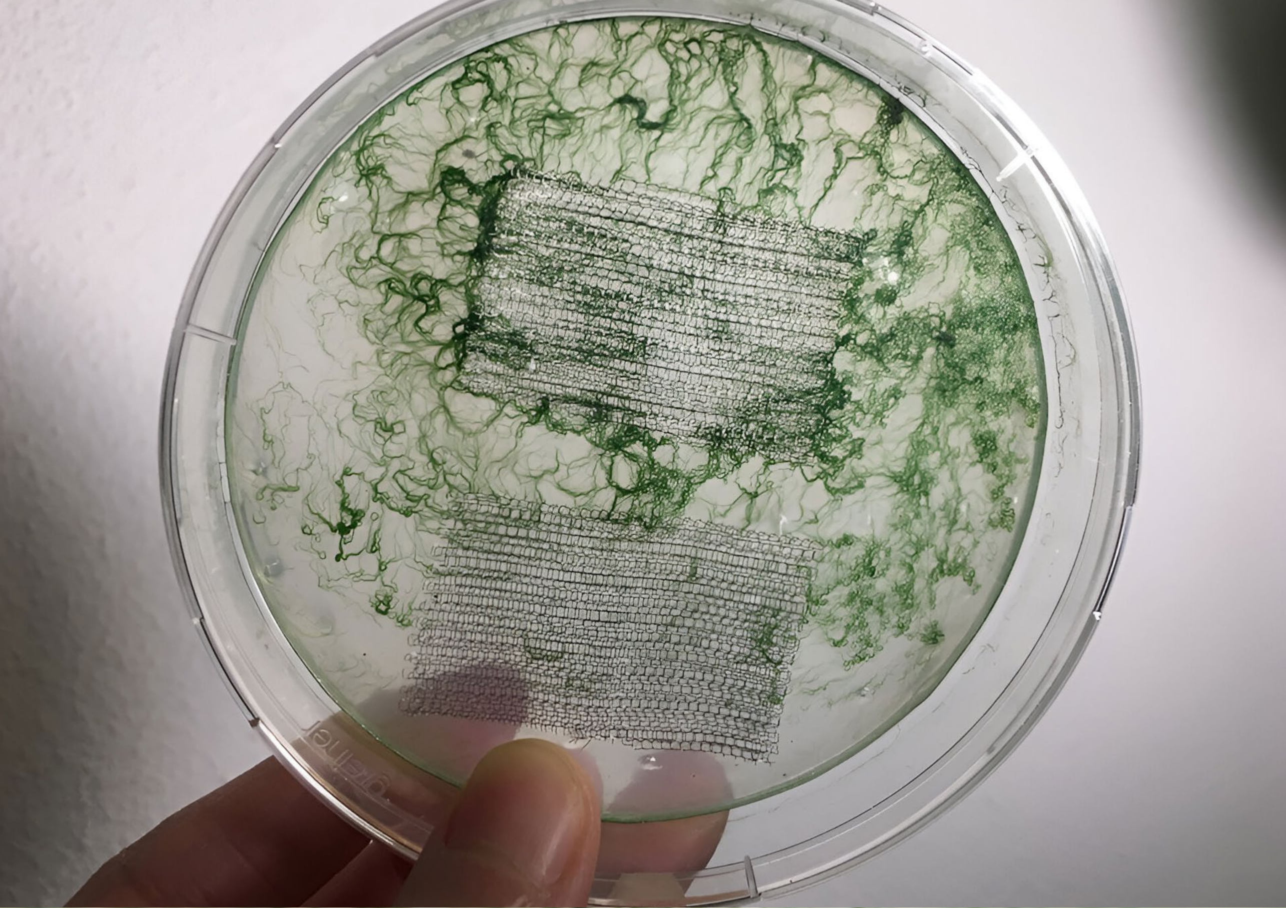


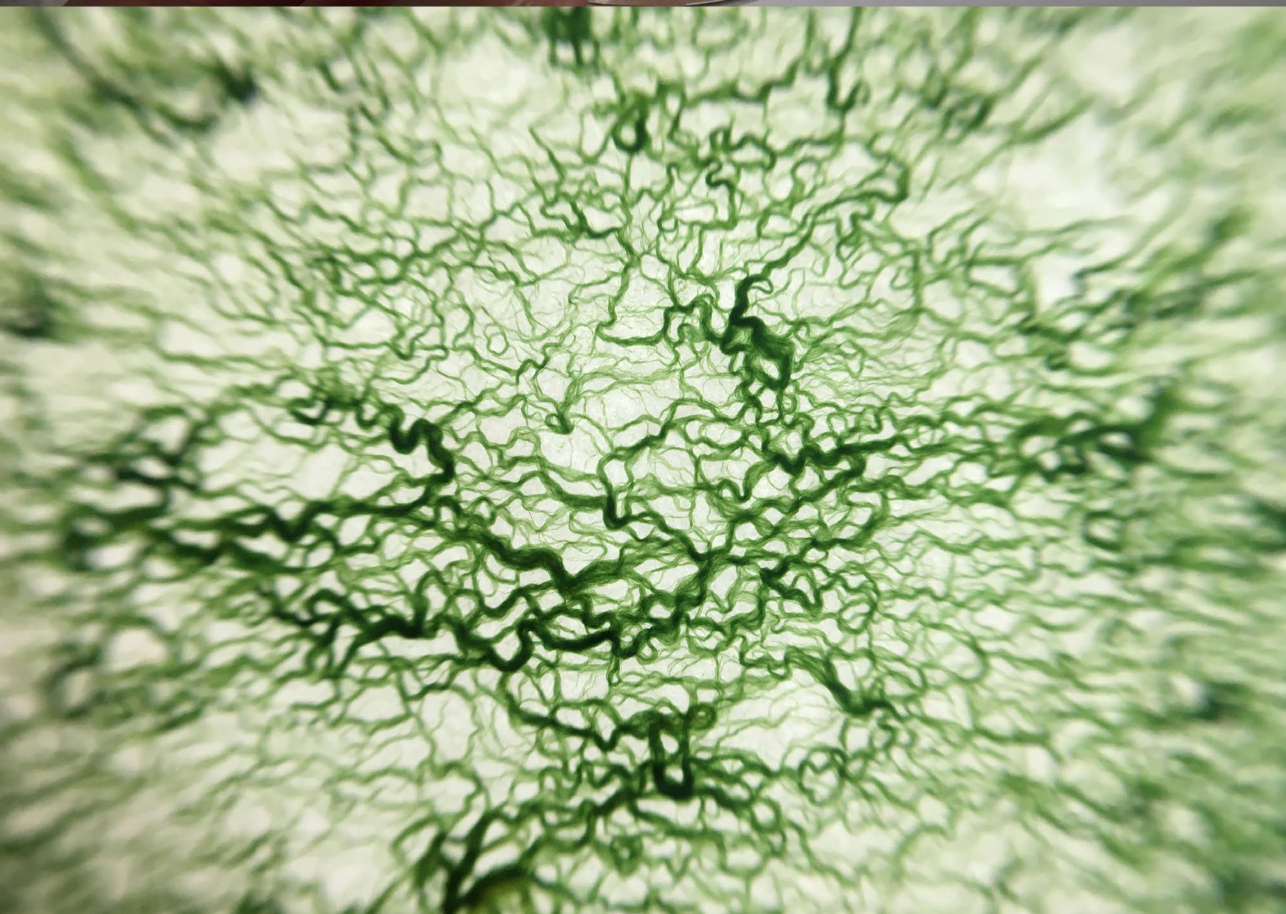
One morning, I noticed a torus formed by the Spirulina, wondering what they were trying to “say.”

If birth and life is to be celebrated, so should decay, change,
comtamination and death. The microbe whispered uncertainty,
its hues dimmed, its vigor faltering.
I lingered, patient, to see its fate unfold.









4 Design Experiment I Designing with Human-microbe Temporal Dissonance

"Patterns of unintentional coordination develop in assemblages. To notice such patterns means watching the interplay of temporal rhythms and scales in the divergent lifeways that gather."

—Anna Tsing

This chapter presents the first design experiment, bringing both a conceptual and a technical lens to the exploration of materiality in fostering care relations between people and microbes in and through living artefacts. A key concept introduced in this chapter is temporal dissonance which refers to the "time lag" typically experienced by humans in noticing the gradual and subtle shifts in the metabolism of certain microbial species mobilised in biodesign. This temporal dissonance can disrupt the fluency of interactions and may hinder timely care for microbes in living artefacts.

To address such challenge, the chapter instantiates how dynamic materials can be utilized to help humans notice cyanobacteria's temporalities through a cyanobacteria based living interface—the Cyano-chromic Interface. It surfaces photosynthesis of cyanobacteria (Synechocystis sp. PCC6803) through monochrommatic changes of an electrochromic (EC) material composite. Grounded in temporal characterization of the interface and its design primitives, the chapter explores imaginary artefacts and scenarios to examine 1) how the interface can be tailored for diverse functional and experiential outcomes, and 2) how the interface facilitates reciprocal human-microbe relationships within and through living artefacts.

This chapter was originally published in the Proceedings of the 2023 ACM Designing Interactive Systems Conference (DIS2023)—an annual venue that brings together diverse communities across design and interaction. Researchers working in biological design, biological human-computer interaction (HCI), critical design, and sustainable and ecological HCI actively contribute to this conference. In recent years, there has been increasing interest in designing with living systems as a novel, sustainable, and regenerative means of reimagining human-world relations. Within this context, the cyanobacteria-based living artefact is framed as an interface—an active mediator facilitating emergent interactions between humans and microbes. The chapter highlights contributions and implications for both design and HCI communities engaged in working with living organisms. References to "this paper" pertain to the original publication, and the chapter retains the structure and formatting conventions required by the conference.

This chapter is based on publication: Jiwei Zhou, Raphael Kim, Zjenja Doubrovski, Joana Martins, Elisa Giaccardi, and Elvin Karana. 2023. 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). Association for Computing Machinery, New York, NY, USA, 820–838. https://doi.org/10.1145/3563657.3596132 [1].

4.1. INTRODUCTION

Distinct biological affordances of microbes offer unique functional advantages in biodesign, such as sensing and displaying, purifying, and energy-generating capabilities. As such, they have been the subject for much discourse in HCI [2], in the design of novel living media interfaces [3] [4] [5], sensing devices (e.g., [6][7]), ambient displays (e.g., [8][9]), public art installations (e.g., [10][11] [12]), and games (e.g., [13][14][15]).

As one of the most abundant and diverse life forms on earth [16], microbes play an intrinsic role in almost every natural cycle, supporting the existence of all higher trophic lifeforms, and the health of the global climate [17]. Also for us humans—one of the many co-habitants existing on the planet—our microbial "companion species" [18][19][20] have also been, and will continue to, profoundly shape the ways in which we live and experience the world.

4.1.1. TEMPORAL DISSONANCE AND ALIGNMENT WITH MICROBES

As we recognize the value of microbes in inspiring the design of novel interactive systems, "bringing their livingness to our senses" ([21], p.45) is important. However, there may be challenges involved with the surfacing [22] process, due to technical constraints, of microscopic size and the apparent slowness in response to stimuli. In this paper, we tap into one such challenge, namely "temporal dissonance", that exists between humans and microorganisms, as one of the initial hurdles that designers need to overcome.

Multiple biochemical reactions take place in a living organism as part of their metabolism. These processes can assume multiple aesthetic expressions in living artefacts over time, in the form of changes in colour and pattern, etc. (i.e., living aesthetics [21]). However, as such changes are often minute, we may struggle to adequately perceive them with sufficient sensitivity. To further illustrate our point, we analyse the phenomenon of oxygenic photosynthesis - a ubiquitous process in plants and a group of microbes including cyanobacterial species (e.g., *Synechocystis* sp. PCC 6803 [23])—which has been crucial for Earth's transition to the present oxygen-rich atmosphere [24]. Unaided human perception of accumulating chlorophyll–a green-coloured indicator of cyanobacteria growth rate—is difficult (if not impossible) to achieve in real time, due to the granularity of the biochemical processes involved. Hence, if there is a persistent disruption in the organisms' metabolism, which would potentially affect its photosynthetic activity—humans would only notice this a couple of days later, when the colour turns pale, which might be too late to effectively act upon. We call this a temporal dissonance; a type of mis-alignment of temporalities between microbial metabolism and human senses. Moving forward, we argue that such type of temporal dissonance would hinder humans from timely noticing of microbes, which may pose challenges to fluency of interactions [25][26][27] with living artefacts and potential barriers towards attending to their vitality. Focusing on the aforementioned cyanobacterial species, we therefore investigate the possible scientific and designerly ways of aligning temporalities between humans and microbes, bringing imperceptible changes in microbial metabolisms more noticeable to humans. To achieve this, we propose a multifaceted approach, starting with immersing ourselves into the life of microbes to initiate the identification of 1) the challenge of temporal dissonance, 2) a surface-able metabolic activity of the microorganism, 3) an appropriate complementary media that would facilitate in addressing such challenge. Following this, we designed and characterised an interface through which the complementary media is synergized with the microorganism to achieve a temporally-aligning interface, which was subsequently imagined and situated in everyday living artefacts.

4.1.2. CONTRIBUTIONS OF THE PAPER

This paper introduces a novel microbial interface that aligns temporalities of humans and cyanobacteria—which we call the *Cyano-chromic Interface*. It consists of cyanobacteria and an electrochromic (EC) material—an electricity-driven and monochromatic display that manifests the gradual and minute shifts during cyanobacterial photosynthesis, at a more perceivable rate and magnitude. By presenting design primitives of the interface, grounded through scientific characterisation, we offer designers starting points for living artefacts that can be situated in diverse use contexts through configurations of their components. We discuss how the interface can be tuned for diverse functional and experiential outcomes in living artefacts. Through the generated application concepts we demonstrate the potentials of the interface towards fostering reciprocal human-microbe relations in everyday scenarios.

4.2. RELATED WORKS

4.2.1. DESIGNING MICROBIAL INTERFACES

Biological-HCI (also known as “bio-HCI”) [28] is an emerging community within HCI that recognizes the distinct possibilities afforded through the integration of biological materials (e.g., plants, fungi, bacteria) and processes, and explores design possibilities that may open up. A body of research in bio-HCI has emerged, examining the roles microorganisms could play in our everyday lives. These include design frameworks, such as Living Media Interfaces (LMI) [3] and Living Bits [28], and design taxonomies [29] that characterises the computational relationship between microbes and the digital worlds. These corpus of works in HCI include the exploration of microbe-driven applications, including novel interfaces (see, for an extensive overview, [22]), sensing devices (e.g., [6][7]), ambient displays (e.g., [8][9]), public art installations (e.g., [10][11][12]), and games (e.g., [13][14][15]).

In introducing *living artefacts* [21]—artefacts in which the livingness of the organism extends to the "use-time" of the artefact—Karana et al. [21] called for an alternative biodesign approach that foregrounds livingness as a biological, experiential, and ecological phenomenon, which could lead to a more sustainable relationship between humans and living organisms. One of the strategies proposed by the authors has been to frame the process around *living aesthetics*. Described as the way humans experience the type, degree, and duration of change in a living artefact over time (e.g. immediate or gradual changes in colour, form, or function), living aesthetics is positioned as a desirable design element that may evoke meanings, associations, and emotions, but could also be crafted for indicating the organism's struggle or well-being, and eliciting unique care actions in the long run, i.e., facilitating the *mutualistic care* [21] between humans and the living organism. HCI researchers showed practical explorations of tuning and characterising living aesthetics in Living Colour Interfaces [5] and Living Light Interfaces [4]. We aim to extend these growing conversations in biological-HCI, by reporting on our investigations on cyanobacteria (*Synechocystis* sp. PCC6803).

4.2.2. CYANOBACTERIA AS A DESIGN MEDIUM

Cyanobacteria, also known as "blue-green algae", are one of the oldest life forms on earth, with fossil records dating back to 3.2 billion years ago [30]. This group of microorganisms can be present in a vast variety of habitats, from aquatic to terrestrial, including hypersaline, deserts, polar and hot springs [31]. Their capability to perform oxygenic photosynthesis and synthesise organic compounds distinguishes cyanobacteria from other bacteria. As photosynthesizing organisms, cyanobacteria can metabolise with only light, water, carbon dioxide, and other inorganic substances. In order to survive, they constantly absorb sunlight and carbon dioxide while releasing oxygen to the atmosphere, a process called carbon fixation, which is a major component of the global carbon cycle [32]. During exposure to light, green biomass accumulates over time (within a time span of days and weeks), converting the total amount of light absorbed into its living colour. In this process they also generate a small amount of electricity [33][34][35], the design and scaling up potential of which has been explored by [36].

Figure 4.1.: Living artefacts integrating photosynthetic microbes. A. Living Things ©Ethan Frier and Jacob Douenias; B. AirBubble ©Maja Wirkus for ecologicStudio; C. Biogarmentry ©Roya Aghighi; D. Indus by Indus by Dr. Shneel Bhayana, Dr. Brenda Parker and Prof. Marcos Cruz, Bio-Integrated Design Lab, UCL. Photo ©Andy Stagg E. Algae-graph ©Lia Giraud; F. Algae Printing ©Marin Sawa in collaboration with Imperial College London (Peter Nixon and Klaus Hellgard), the printed artifact for electricity generation in collaboration with Andrea Fantuzzi.

Photosynthetic microbes have been integrated in several recent designs (figure 4.1) that function as part of energy converter [37], interactive air-purifying playground [38], air-purifying garment [39], outdoor water-detoxing tiles [40], light-responsive image display [41], and electricity producing wallpaper [36]. However, their potential as an interactive living media for HCI hasn't been explored to date. Following an existing technical framework [36], we focus on cyanobacterium *Synechocystis* sp. PCC6803 as a relatively simple photosynthetic microbe and a model organism in science, as a starting point for our research. Inspired by the notion of living aesthetics, we first turn our attention to the peculiar ways cyanobacteria change and evolve over time; its temporality.

4.2.3. TEMPORALITY OF MICROBES IN HCI

An historically extensive corpus of research on temporality in HCI has been driven by the idea of improving computer system response times (e.g., reducing input-output latency) under the premise of enhanced machine efficiency and use productivity [42]. Contrastingly, other scholars have explored divergence of temporalities[13, 43–48], such as the concept of "slow technology" [44], which re-positions technologies as a tool and a medium towards fostering slow interactions in our everyday lives. By doing so, they argue, slowness would invite opportunities for reflection, solitude, mental rest, and contemplation (e.g., [49][50][45][51][52]). In addition, in design literature, one thread of discussion concerns the notion of *Temporal Design* [53] acknowledges the multiple dimensions and narratives around time, towards their implementations beyond the aforementioned ends.

Scholars exploring living organisms as an interactive "bio-computational material" [54][3] have proposed possible contrasting ways in which the non-human temporalities of microbial species could be remedied through design. On one hand, some have framed microbes' slowness as a design opportunity (e.g., [55][56][46]), a tool for human conditioning (e.g., patience [57]), and as a productive design element that could be integrated towards enhancing user experiences (e.g., [13][58][57]). On the other hand, some have framed the slowness of biological response and the resulting temporal misalignment between humans and microbes as a challenge for interaction design. They see it as a negative feature that may compromise the fluency of interaction and associated user experiences (e.g., [59][14][11][15] [12]), whilst exploring hardware and software solutions that could enhance or augment the organism's response to stimuli (e.g., [60]).

We recognize the unique temporal expressions of cyanobacteria, i.e., its living aesthetics, and how this could be unlocked as a design potential in living artefacts (as explored by other biodesigners discussed in the previous section). However, whilst we acknowledge that utilising slowness and temporal dissonance in their natural form can offer alternative experiential opportunities for the prospective users of living artefacts, doing so may not necessarily prove beneficial for microbes' survivability.

Approaches to tackle temporal dissonance in Bio-HCI

Researchers explored theoretical frameworks and approaches to temporality that are also beneficial for living organisms, either by translating microbiological phenomena [22] or environmental data, to more human-comprehensive forms [61-64]. In *Tardigotchi* [65], a water bear's temporality is revealed to humans in real-time through a displayed digital microbial avatar that communicates whether the real water bear is hungry or satisfied. Text messages remind the user to feed the microbes on time. Similarly, *Nukabot* [66] is an artefact that communicates the needs of food-fermenting bacteria, through the use of a vocal user interface and cultural symbols, that are both designed to emotionally appeal to the human users. By doing so, the users are encouraged to regularly stir the fermenting bran as a way to deliver regular care to the microbes in order for the microbes to continue produce food for humans (i.e., mutualistic care). These two designs both facilitate temporal alignment towards care, through timely reminders that would maintain their respective microbial vitality. Other scholars exploring temporal alignment include Armstrong[67], whose work *Active Living Infrastructure: Controlled Environment (ALICE)* [67] proposes a platform with which humans can engage in real-time "conversations" that are sensitive to fluctuations of microbial physiology. Delivered through the use of electrical signal sensing, digital simulation with artistic representation ([67], p.11-12), the artefact calls for a more sensitive approach towards the seemingly invisible and slow microbial worlds.

In this paper, we have extended these existing HCI explorations by designing a *Cyano-chromic Interface*, to address the temporal dissonance between humans and cyanobacteria. Similar to *ALICE*, we aim to translate fluctuations in microbial metabolism (electrical signal of cyanobacteria) to be perceived by humans, with enhanced sensitivity. In our case, however, the means with which the translation is displayed are not digitally simulated. But rather, they are manifested through its materiality, specifically with electrochromic visualisation involving colour change, an alternative avenue for interpretation. Furthermore, the primitivity of the interface is given prominence, as building blocks that are open for customised artefact construction whilst yet to be highly configured.

The Cyano-chromic Interface, with its sensitive, chromatic, and customisable features, would naturally require multi-phase development, consisting of scientific grounding and design instantiations. In the following section, we outline these phases in further detail.

4.3. CYANO-CHROMIC INTERFACE

4.3.1. METHODOLOGY

Our research, informed by material-driven design [68], combines different design, science and engineering techniques to help zoom in and out the micro-organism—cyanobacteria—for its thorough understanding and to explore the relationships between the various material components of the interface. We started with a first-person study by the first author, during which the author lived with cyanobacteria for three months. This part concludes with the insight of the design challenge of temporal dissonance and a technical inquiry to identify a potential complementary media that can be utilised to timely surface cyano-bacterial metabolism, and thus address the challenge. Second, an interface was designed by coupling the chosen media with cyanobacteria. Then we conducted controlled lab experiments to characterise and validate the working principle of our interface, which provided the foundation for the next step of generating design primitives. And finally, the primitives were utilised subsequently in generating and illustrating the application concepts.

4.3.2. FIRST-PERSON LIVED EXPERIENCES WITH CYANOBACTERIA

To become immersed with cyanobacterial life, as a way to familiarize with their temporality, the first author lived with the cyanobacterium *Spirulina platensis* (a commercially accessible strain and a substitute for *Synechocystis* sp. PCC6803) for three months in a (home) design studio.

The cyanobacterial culture and its nutrient solution were contained in a transparent glass bottle. During the author's daily encounters with cyanobacteria, the culture was divided into multiple glasses, and placed on a south-west facing window sill. Carefully formulated nutrients were added to placate the needs of the microbial companions at intervals which were deemed most suitable through observing culture density. Light qualities had a substantial impact on the health of the culture: if the culture was under constant and moderate light in the day, its colour would appear greener over days, until a dense, dark green colour over weeks; due to growth and reproduction of cells (figure 4.2, A). However, during the time of cohabitation, a few of the cultures were damaged, when they were exposed to direct sunlight for too long. The culture colour became yellow-brown in a few days (figure 4.2, B), which could not be revived. On reflection, these damages could have been avoided with a timely reminder that would signal the struggles of the microbes to the author, who would have taken appropriate care actions.

The lived experiences thus helped us to identify our design challenge—a temporal dissonance between humans and cyanobacteria—demonstrated by the fact that the vitality of cyanobacterial cultures is usually noticed late. Furthermore, it inspired us to focus on photosynthesis as the metabolic activity that we aimed to surface. We envision that a complementary media, which could help the organism express its timely photosynthetic well-being, would help to address this temporal dissonance.

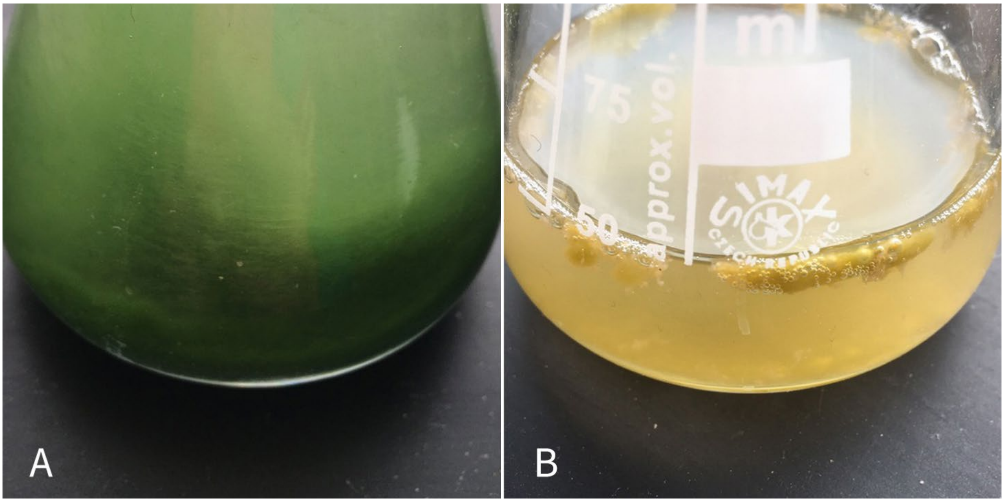


Figure 4.2.: Cyanobacteria cultures at different conditions A) a healthy culture with a dark green hue B) a culture that has been damaged by direct sunlight characterised by its yellow-brown appearance

4.3.3. THE INTERFACE

This section presents the design and the making of a temporal-aligning interface, which we call *Cyano-chormic Interface*. We focused on light intensity as the influence factor for cyanobacteria photosynthetic health, which we aimed to timely surface. This was enabled by using a complementary media—namely electrochromic material—with which the architecture of the system was designed, and its characterization was conducted, in the development of Cyano-chromic Interface.

Eletrochromic Material as Complementary Media

We filtered through a few potential media (within the scope of smart materials and meta-materials) with the following criteria: (1) it directly receives input (such as oxygen, electrons, etc.) from cyanobacteria cells to function; (2) the output modality has similar sensorial qualities as living aesthetics of the organism (i.e. colour change); and (3) it can be adapted for integration in everyday artefacts. Based on these criteria, we ultimately focused on one media based on electrochromism, a phenomenon in which a material displays changes in colour or opacity in response to an electrical stimulus [69]. For this, we used an electrochromic material (EC)—PEDOT:PSS (poly(3,4-ethylenedioxythiophene) polystyrene sulfonate) [70], which can be integrated into a sheet material that can switch colour from light blue to dark blue upon electrical stimulation, received from cyanobacteria. Since the microbe can generate twice the amount of electricity under light conditions than in the dark [36], we harnessed such a difference in electrical current to trigger the EC displaying different shades of blue.

System Architecture

The interface is designed to allow the EC material to be stimulated by electrons generated during cyanobacterial photosynthesis, based on a technology called biophotovoltaics (BPV). Through assembly of BPV systems, electricity generated by the microbe can be utilised to power external devices. For the component that hosts cyanobacteria (i.e. cyano unit in figure 4.3), we tailored an existing technical framework of BPV construction [36]. The protocol suggests using an ink-jet (bio)printing method for fabricating the BPV system on a paper substrate. In this method, anode and cathode conductive inks are printed onto the paper, followed by the printing of the bio-ink containing cyanobacterial cells. Through electron transfer between anodes and cathodes, electrical current can be harvested in a closed circuit (figure 4.3). We adopted the protocol's paper-based design for constructing the cyano unit, due to its compact size and interaction potentials. Extending the approach of [36], we adopted a direct-ink-writing (bio)printing (an extrusion-based additive manufacturing method) [71] for fabrication of the cyano unit. To ensure brevity of this paper, we have moved further technical details and construction methods to Appendix.

The architecture (figure 4.3) of the Cyano-chromic Interface consists of four major components: 1) Cyano unit(s), where cyanobacteria are located, 2) EC unit(s), and 3) the paper substrate, 4) hydrogel sheets, which supplies nutrients and water to the microbe. The cyano units need to be exposed to light, under which their photosynthetic activity can generate electrical current supplying to the EC units in a closed circuit. Figure 4.3 includes an example primitive of the EC unit, consisting of two fields of pigment, one becoming dark blue upon electrical stimuli.

As in figure 4.3, the cyano unit can be configured in two ways: coplanar (figure 4.3, A) and stacked (figure 4.3, B). In a coplanar configuration, the anode and cathode materials are printed on one substrate, which makes the interface more compact, pliable, and allows for precise design and customization of electrodes. In a stacked configuration, in contrast, the anode and cathode components are vertically layered, which makes the interface easier to assemble, and thus are usually used for initial performance characterisation.

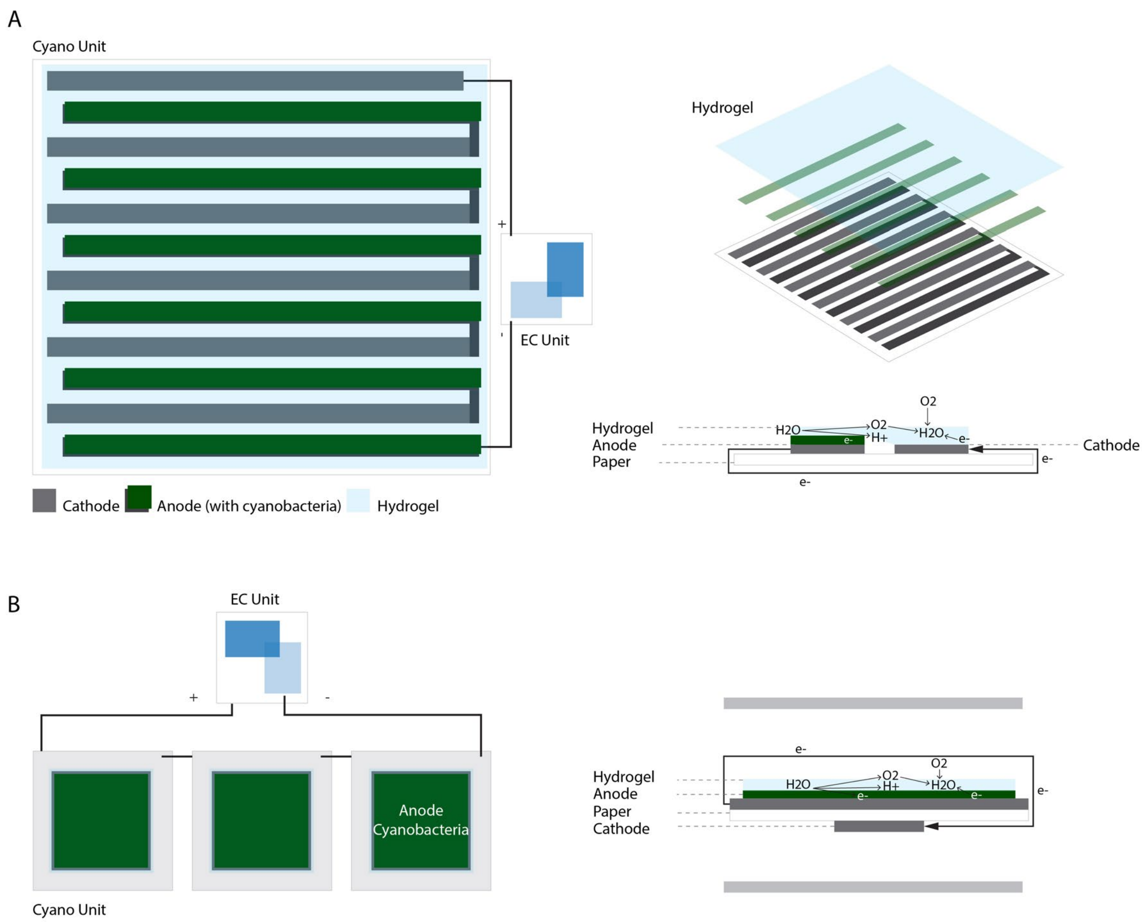


Figure 4.3.: System architecture of the Cyano-chromic Interface, illustrating two possible configurations. A: Coplanar configuration enabling exposure of both electrodes in a single surface plane. B: Stacked configuration consisting of electrodes on layered surface planes.

4.3.4. CHARACTERIZATION OF THE INTERFACE

To validate our interface design, we undertook several characterization tests of the cyano unit, EC unit and the interface performance, which are outlined below.

Cyano Unit Characterization

Characterization of the cyano unit was based on the existing protocols presented by [33, 34, 36]. Potential output of the stacked cyano unit (figure 4.4, A) was measured by loading an external resistance (100 kOhm) over light and dark periods (1hour/1hour, illumination in the light period at 100 µmol · m−2 · s−1). Figure 4.5 shows the responding potential output to light and dark situations in 2.5 cycles. The result suggested that the cyano units can periodically generate relatively higher electricity in the light, than in the dark conditions. No negative control (with only the culture medium) was performed because we reset the baseline current in every measurement by draining the stock current until stabilization.

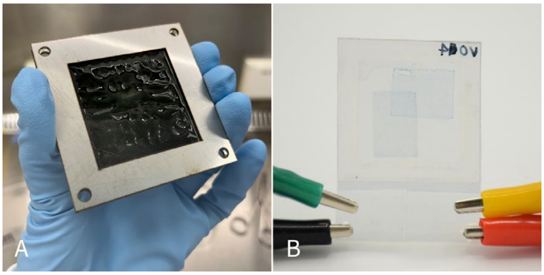


Figure 4.4.: An assembled stacked cyano unit (A); An assembled EC unit (B)

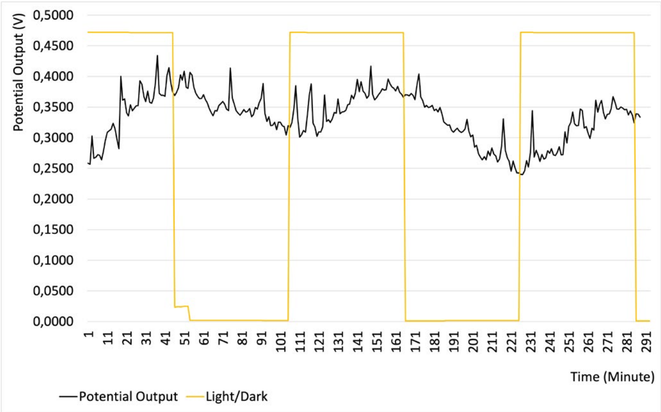


Figure 4.5.: Voltage output to an external resistor (100k Ohm) over two and half light/dark cycles (1hour/1hour, illumination in the light period at 100 µmol · m−2 · s−1)

EC Unit Characterization

This characterization involved testing the degree and duration of colour change of the EC unit based on different supply voltage and current. The colour change has two phases: charging and stabilizing. In the charging phase, the EC material draws a peak current upon its connection to the power supply, and drops to a lower value within a few seconds to reach a stabilizing phase. The current remains a low value afterwards. Each EC unit has its own internal resistance R(ec) that consumes a minimum amount of energy in the stabilized phase. The end state voltage on the EC can be summarized by the following equation:

$$U(end) = I(stable) \times R(ec) \tag{4.1}$$

The EC unit used in the test was composed of two visually overlapping rectangles on opposite electrodes (figure 4.4, B); when charged, the rectangle on the anode side becomes darker. A test was done to understand whether current supplied by cyano units gets transferred to the EC can stimulate observable colour change. To sustain low peak current which cyano units can potentially supply, a variable resistor was connected in series to the EC unit, and adjusted to ensure that the current supplied to the EC unit was between the ranges of 0-10 μA. The EC unit darkened its colour with a greater change at a higher peak current supply (figure 4.6). The colour change duration ranged between 9 to 13 minutes.

To conclude, the colour difference of an EC unit driven by the simulated cyano-unit currents was perceivable, which provided adequate technicality to our follow-up investigation on characterizing the overall interface performance.

Cyano-chromic Interface Characterization

Four cyano units were connected in series (figure 4.7) to an EC unit and placed in an incubator (with Relative Humidity of 98%) with mounted white LEDs. The cyano units were first kept under darkness for 1 hour and then exposed to illumination of 100 μmol · m−2 · s−1 for 1 hour. Colour states of the EC unit were photographed before and after each period. At the end of the light period, the EC unit increased its colour intensity (figure 4.8).

The colour change from dark to light period was observed to be subtle (as shown by figure 4.8). However, we argue that by tuning the components in the system, one can potentially obtain a more prominent colour change, for instance, by

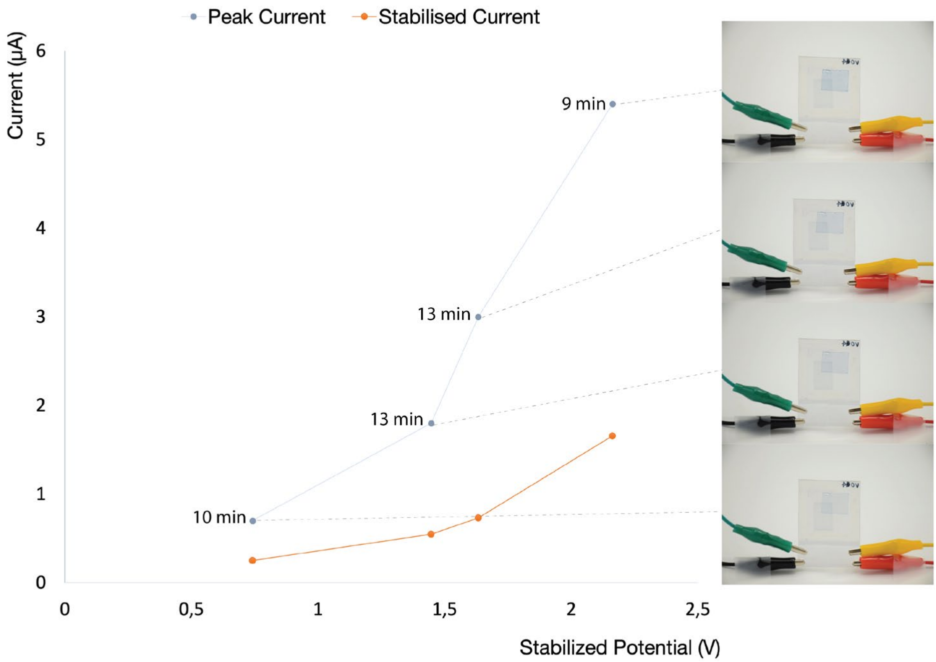


Figure 4.6.: Understanding how peak current influences colour changing time and end state colouration

increasing the number of cyano units [36], cell density [33], conductivity of electrode materials [36]. For instance, by increasing the number of cyano unit from 4 to 20, one can achieve 2 volts to power the EC unit under the light condition (as in our test), and 1 volt under the dark condition. According to figure 4.8, this would make the colour difference between light and dark periods more prominent.

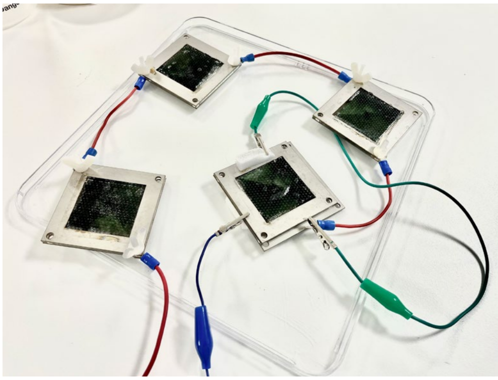


Figure 4.7.: Four cyano units are connected in series

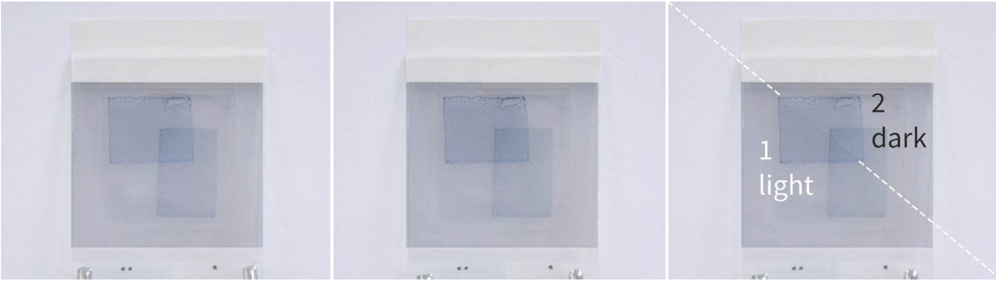


Figure 4.8.: Response of the cyano-chromic interface to dark-light conditions. The top-left rectangle of the EC material changed colour from lighter to darker blue from dark (left) to light (middle) period. The colour comparison (right) of the EC material of the two states.

4.3.5. PRINTABILITY OF THE CYANO-CHROMIC INTERFACE

To further help the grounding of interface design, we continued to demonstrate the printability of cyano-unit in a coplanar configuration (figure 4.3, A). Anodic and cathodic conductive inks were printed onto a robust watercolour paper (300g /m2) substrate, in a semi-staggered and semi-overlapping pattern (figure 4.9), to enable both polarities in a single surface plane. As a last step, the bio-ink was printed onto the anode area. This configuration offered high surface area for printing, whilst providing a flatter and thinner (and potentially more flexible) area for the interface to function, which inspired the generation of our design space.

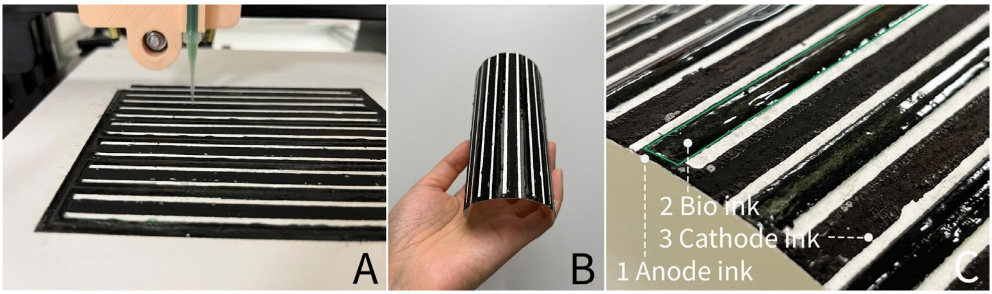


Figure 4.9.: A fully printed coplanar cyano unit, on paper (B); Printing process (A); Close-up view (C): 1) anode ink 2) cyanobacteria in hydrogel 3) cathode ink

4.4. DESIGN SPACE

In this section, we present a design space for the Cyano-chromic Interface, illustrating its potential to be integrated in everyday artefacts. Here, we explore the possible ways in which temporal alignment between the human and the microbe, aided by the interface and its associated designs, could help to address challenges that stem from temporal dissonance. We begin the chapter with some design primitives of the Cyano-chromic Interface to provide the general backdrop for interface variations and application concepts.

4.4.1. DESIGN PRIMITIVES

We exemplify design primitives of the interface, including the cyano unit, the EC unit and interface configurations, which can be multiplied, combined and oriented for various functions and aesthetics.

Cyano Unit

The cyano unit can be customized according to the desired pattern and printing method. The width of the electrodes should be within the approximate range of 1 to 6 mm, to allow for efficient proton exchange [72]. Area size ratio between the anode (green) and the cathode (black) should be roughly 1:1. We provide some examples of anode-cathode shape pairs (no.1 - 5 in figure 4.10).

EC Unit

The EC unit can be varied in qualities of colour change, including intensity, gradient, and speed [70]. We provide five examples of EC shapes, for various visual effects (figure 4.10 top left, numbers 1 to 6). For example, the 5th shape (in figure 4.10) shows a “levelling up” effect; with current supplied, circles can change to dark blue in sequence. Through the use of capacitors that would store the electricity generated by the cyano unit [36], one can supply periodic bursts of energy to the EC, achieving a blinking effect (figure 4.10, no.6).

Interface Configuration

Interface configuration determines the distribution of sensing (cyano unit) and displaying (EC unit) components. In a decentralized system, each EC unit is powered by a localized group of cyano units, reflecting on the photosynthetic activity of a specific region, thus making the system deconstructable and re-configurable. This allows for locally adaptive interfaces that can be customised to meet situational requirements, when uneven distribution of light needs to be indicated. In contrast, in a centralised system, the EC units reflect the overall photosynthetic activity of cyano units despite their respective locations.

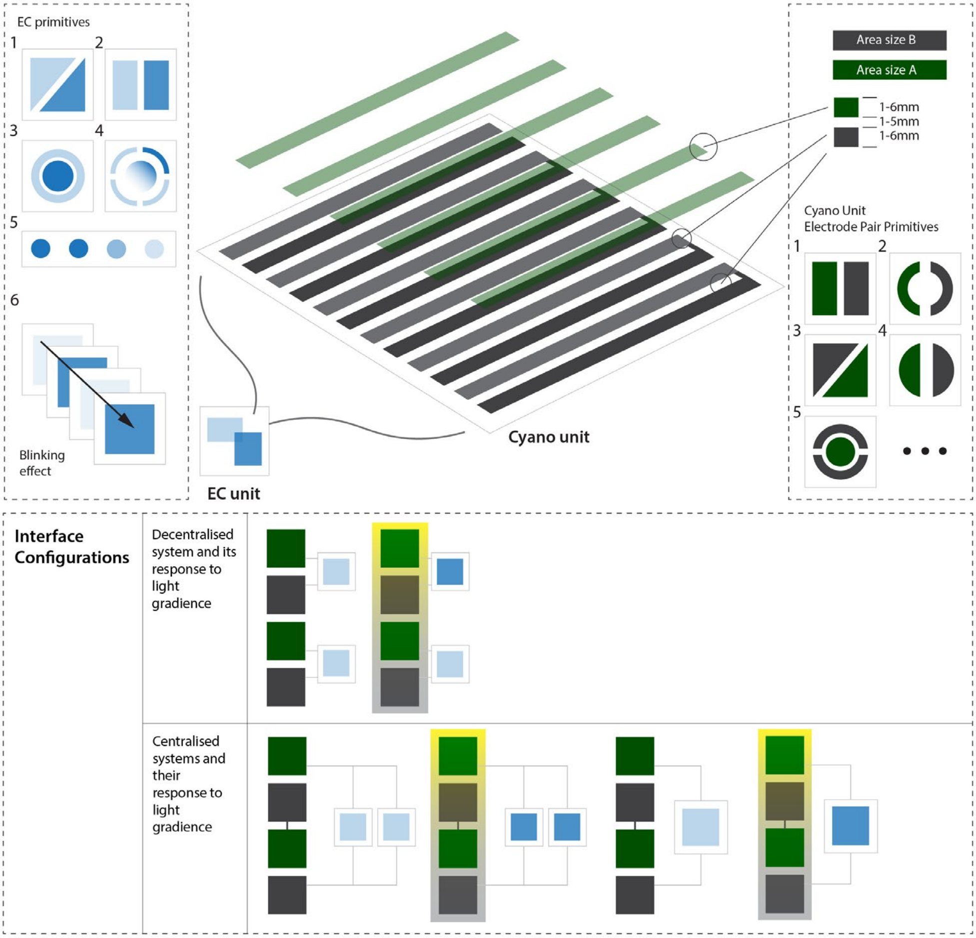


Figure 4.10.: Design primitives of the interface: Variations of cyano units, EC units, and interface configurations

4.4.2. POSSIBLE ACTIONS TO INFLUENCE LIGHT CONDITIONS

Due to the paperness of the interface, visually-triggered, light-adjusting interactions can happen in different ways (figure 4.11). In return, metabolism, and its resulting colour change of the interface, can be tuned. Possible actions include folding, rolling, covering, and moving, as well as adjusting light sources (such as drawing curtains, turning lights on and off). Amongst them, the first four are direct interactions with the paper substrate, and the last is an indirect interaction with the surrounding environment.

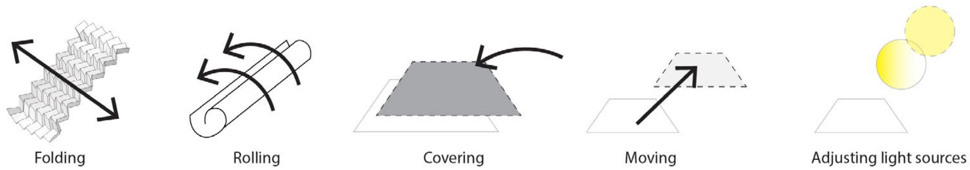


Figure 4.11.: Possible actions that influences light conditions of the interface

4.4.3. INTERFACE VARIATIONS

Here we show four possible coplanar interface variations (figure 4.12), where design primitives are structured for diverse expressions. Primitives in these examples can be interchanged, multiplied and re-distributed for creative configurations; each interface can be multiplied and re-distributed, to allow for decentralised sensing and actuating. We will further elaborate how they could be tailored to function with four applications in the following section.

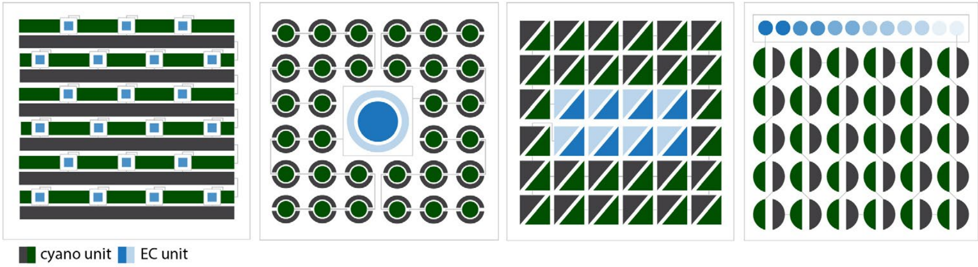


Figure 4.12.: Coplanar Interface Variations. 1) striped parallels of Cyano units, with pixelated EC units, showing collective effects 2) circle patterned Cyano units, with an EC unit at the centre 3) triangular patterned Cyano units, with EC units at the centre 4) circle patterned Cyano units, with EC unit at the top, showing levelling-up effect

4.4.4. APPLICATION CONCEPTS

This section outlines a selection of possible applications that integrates the interface as part of various design outcomes. Overall, we wanted the concepts to bring the interface to life: demonstrating potential implementations of its temporal alignment capability, through situating it within the realms of our everyday lives. More specifically, we envisioned how the possible outcomes of this timely noticing of microbes would look like in terms of fostering human-microbe interactions that are not only utilitarian, but also reciprocal. The concepts represent the Cyano-chromic Interface operating under a variety of situations based on different light sources, such as natural sunlight, artificial indoor light, and a combination of both. The concepts are briefly described below supported by renderings presented in realistic contexts.

Daylight Log

Human well-being is subject to natural daylight that is based around the rotation of the Earth. However, the change of daylight qualities in our living space is often unacknowledged. The Cyano-chromic Interface can respond to periodic fluctuations of (natural) daylight within its situated environment through noticeable colour change of the EC units. In Daylight Log (figure 4.13), at low light conditions, its EC units fade its colour, "requesting" humans to address the situation by unfolding the artefact that would expose the cells to more light (figure 4.13, middle). It reveals the miniscule shifts in light conditions within a matter of minutes, which provides a suitable time window, quick enough for delivering adequate care for the microbes but gradual enough to allow for being mindful of daylight range and fluctuations. The interface also allows the cyanobacteria to leave a visible trace [73][5], as a form of accumulated green biomass, for humans to notice and to reflect on their performances with the artefact over days, weeks, and beyond (figure 4.13, right). By doing so, humans allow themselves the opportunity to reflect and to celebrate their effort in long-term care for the microbes. This concept helps to imagine the design space where temporalities of the interface can be leveraged to suit multiple functions (e.g. timely care for microbes) and experiences (e.g. present and retrospective mindfulness), exposing the relations and multiplicity of temporalities [53].

Kids' Hiking Companion

Young hikers often overlook the importance of managing the timing and duration of breaks, which may lead them to over exercise. The Kids' Hiking Companion (figure 4.14) acts as a tunable timer that reminds the hikers to take regular short breaks, especially when hiking under intense sunlight. In that situation, the Cyano-chromic Interface would blink faster (figure 4.14, middle), signalling for a break time and the need for cyanobacteria to be shaded. Within a few minutes of the break, the interface would slow down its blinking (figure 4.14, right), thus reminding the hikers to continue with their trail. The interface could be positioned at body parts (e.g., upper chest) of the hiker, which would ensure sunlight exposure and adequate noticing by the wearer or their guardians. The concept addresses the needs of both the human and the cyanobacteria, allowing both to "pause" from their respective activities, whilst aligning their respective break times. It demonstrates the applicability of the interface for a variety of outdoor activities that would need various timely intervals of (collaborative) rest and recovery.

Figure 4.13.: Daylight Log: at low light conditions, its EC units fade its colour, "requesting" humans to address the situation by unfolding the artefact that would expose the cells to more light. The interface also allows the cyanobacteria to leave a visible trace for humans to notice and to reflect on their performances with the artefact over days, weeks, and beyond

Figure 4.14.: Kids' Hiking Companion: Under intense sunlight, the Cyano-chromic Interface would blink faster, signalling for a break time and the need of cyanobacteria to be shaded. Within a few minutes of the break, the interface would slow down its blinking, thus reminding the hikers to continue with their trail

Circadian Navigator

Night time exposure to artificial light—such as those emitted by monitor screens of electronic devices—can disrupt human circadian rhythms, and could compromise our mood and sleep quality. Interestingly, such night time exposure to artificial light can also disturb circadian rhythms of cyanobacteria [74]. As an artefact to be worn around the eyes, Circadian Navigator (figure 4.15) invites users to undertake a shared journey with the navigating microbes, as a way of embracing darkness together and collaboratively steering away from screen use. As the cyano unit of the artefact reacts to the light emitted from the screen, the EC component would darken its colour which would subsequently restrict the opacity of the worn lenses (i.e., visibility) (figure 4.15, middle), nudging the wearer away from their screen use. The artefact illustrates the potential of Cyano-chromic Interface towards facilitating healthy night practices; minimising night time artificial light engagement and thus aiding better (human) mood and higher quality rest.

Mushroom Shade

As part of the domestic food-web, growing and harvesting mushrooms at home helps in reusing food waste, towards self-sustainable and localized food production endeavours. The mushrooms usually need a moderate light environment for healthy growth, and should avoid direct sunlight. Mushroom Shade (figure 4.16) explores the Cyano-chromic Interface's ability to provide a chromatic "shield," designed to regulate light conditions for the mushrooms. Under excessive sunlight, the EC unit of the interface would darken its colour, casting a protective shadow onto the fungi body underneath (figure 4.16, right). By such visual signalling, the interface also aids to communicate environmental light changes to humans. As such, users can provide care to the mushrooms in a delicate way, by "planting" the Mushroom Shade above each cluster of fruiting bodies (figure 4.16, middle), or moving both species to a more shaded place. The Mushroom Shade illustrates the potential of Cyano-chromic Interface in engaging users in noticing not only cyanobacteria, but also the growth of food-producing fungi, thus carefully managing light and shadows that nourishes both microbial species.

Figure 4.15.: Circadian Navigator: As the cyano unit of the artefact reacts to the light emitted from the screen, the EC component would darken its colour which would subsequently restrict the opacity of the worn lenses (i.e., visibility), nudging the wearer away from their screen use.

Figure 4.16.: Mushroom Shade: Under excessive sunlight, the EC unit of the interface would darken its colour, casting a protective shadow onto the fungi body underneath. Users can provide care to the mushrooms in a delicate way, by "planting" the Mushroom Shade above each cluster of fruiting bodies.

4.5. DISCUSSION

With their unique abilities to sense and adapt to environmental stimuli, microbes offer a wide range of possibilities for design and HCI. However, living with microbial living artefacts often faces the challenge of temporal dissonance that hinders timely notice and fluency of interaction. We introduced the *Cyanochromic Interface*, as one way to address such a challenge by aligning temporalities between humans and microbes. The interface is designed to respond to photosynthetic activities of cyanobacteria (influenced by environmental light conditions) with reduced time lag, by changing its colour and intensity at a rate that can be made more noticeable to humans, through an electrochromic (EC) component. We showed that the Cyano-chromic Interface effectively surfaced cyanobacteria's metabolism (photosynthesis) and speculated on the situations in which artefacts designed based on the interface can help enable reciprocal relationships of humans and cyanobacteria and engage humans to connect and empathise with other-than-human species. We begin to unpack the functional and experiential aspects of the interface, followed by other potentials in extending design spaces for biological-HCI.

4.5.1. TOWARDS TIMELY NOTICING AND CARE FOR MICROBES

On an experiential level, the reduction in time taken to notice photosynthetic activities of cyanobacteria, as technically demonstrated by the Cyano-chromic Interface, opens up a pathway towards experiencing living artefacts that are more responsive to human and environmental inputs. In other words, the interface is a technically eloquent way to placate the so-called "slowness of biology" that has been framed as a design challenge by some HCI scholars (e.g., [55], p.266; [56] p.221; [46] p.2211, [11]; [14] p.3, etc.). At the same time, however, thanks to the cyano unit, the interface preserves the inherent temporality of the microbe, as something that can facilitate and encourage slow interactions; a research topic that has been ongoingly explored in HCI (e.g., [52][58]; [57] p.2). In other words, designers may also consider the interface towards creating slow artefacts towards reflection, contemplation, and patience: Over the course of days and weeks, with healthy (and patient) management of cells, users of the Cyano-chromic Interface would notice an increase in intensity of green hues from the interface, resulting from the accumulation of chlorophyll. This ability of the interface to also visually express photosynthetic well-being of microbes over wider time-spans—here in the ranges of days/weeks—users of the artefacts are given time to reflect and to contemplate on their past relationship in looking after their microbes.

On a functional level, our Cyano-chromic Interface can be framed as a vital component in supporting designs that would enable microbial noticing [75][76] and surfacing livingness [22] that can lead towards delivery of care [77] and the design of mutualistic care [21]. Our proposed applications have emphasised the type of care that is concerned with maintaining the health of cyanobacteria. Taking a remedial and ecological stance towards application of biotechnology, we concur with other HCI scholars (e.g., [67][66][78][65]) in arguing that one of the most pressing areas for application of the living interface, should be targeted towards empathizing and caring for living beings. Not only for the integrated cyanobacteria themselves, but also for mutualistic relationships between living artefacts and humans, and for other-than-human species that make up the diverse ecological assemblages. Moving forward, our proposed applications illustrate several possible ways to solicit care. Several mechanics inherent in Cyano-chromic Interface's operation have been leveraged from the users of our imaginary living artefacts. From its pronounced colour fading in Daylight Log, to a blinkable display in Kids' Hiking Companion, and the light responsive darkening involved in Circadian Navigator, the interface offers choice and adjustability with which designers can implement in eliciting care according to different situations, and multiple species involved in them (showcased by Mushroom Shade).

4.5.2. INTERFACE PAPERNESS AND ITS PERFORMATIVE POTENTIAL

The material attributes of the interface suggests a tangible and interactive way of designing microbial interfaces. As demonstrated from experiment results, the printed coplanar configuration can accommodate the cyano unit of the Cyano-chromic Interface to be 3D-printed in sequence onto paper substrates. This enables multi-situatedness [79] of the interface to be applied in various types of artefacts and situated in diverse contexts, as demonstrated by the diversity of proposed applications. With this we suggest that Cyano-chromic Interface can be a paper-based composite - a type of hybrid material which has been explored in HCI previously for many types of computational composites [80]: e.g., in supporting tangible interactions [81], sensing and actuating [82] [83], generating energy [84] and crafting circuits[85].

As a design material, paper is simple and affordable, whilst offering craft characteristics to technology[85]. Its inherent qualities, e.g., lightweight, flexible, air/water-permeable, rough, porous and absorbent, affords diverse actions [82] both in fabrication time (e.g., print, paint, fold, cut, and glue) and use time (e.g., fold and roll). Due to its porosity and absorbency, print-ability of paper has been widely applied in hosting conductive inks and polymers (e.g., [82][81][83] [85]). In the Cyano-chromic Interface, wet and nutrition-diffused watercolour paper provided bio-receptibility to living cyanobacteria cells. The stiffness and robustness of the paper used, allows repeatable folding and unfolding. Based on this, we designed and incorporated folding interactions in Daylight Log to alter light and shade projected onto the cyanobacteria. If designers want to further increase such performative potential of the interface rooted in its material qualities [86] [87], we suggest exploring various origami [88][89][90] or kirigami techniques [91][92][93], which allows multi-dimensional foldings and stretchings to be integrated into interactions with the microbe. This could make the interface more intuitive in eliciting actions from people towards novel configurations and care practices in the everyday.

4.5.3. TUNABLE INTERFACE TOWARDS DIVERSITY OF OUTCOMES

As we analyse design primitives of our Cyano-chromic Interface, we suggest a further potential offered by the interface, that of enabling designers the possibility to tune the performance of living artefacts. Given its inherent modularity and small size as a building block, the interface helps with calibration of design outcomes through iterative processes of adding, subtracting, and re-distributing. Some designs may require a large surface area to display colour change, whilst some situations may call for its reduction, depending on the needs of its user(s). Surface area of Daylight Log, for example, may need adjusting to address varied individual domestic environments within which the living artefact would be situated. Similarly, high diversity of mushrooms would rely on Mushroom Shade's adjustability to cater for the density and species-specific needs of the fungi.

In addition, configurations of the Cyano-chromic Interface suggest that its tunability may also arise from multiplication and distribution of its constituting design primitives. For example, by adopting either a centralised or decentralised system (as shown in Design Space), the interface can be used to indicate photosynthetic activity of cyanobacteria in two different ways. A centralised system can be applied in scenarios where the holistic activity of a living artefact needs to be noticed and acted upon. In Kids' Hiking Companion for example, EC units indicate overall sun exposure. Localized sensing enabled by a decentralized system is more meaningful in indicating location-relevant "data" of state changes, in a similar way to how meta-materials are applied in sensing local environmental stimuli [94][95]. In short, instead of signalling chemicals [94] or mechanical pressures [95], the decentralized interface would provide opportunities in sensing and responding to regional light differences. A tunable Cyano-chromic Interface would, in essence, empower designers with diversity of processes and outcomes. Tuning living artefacts may thus extend its accessibility to cater for, and to address the diverse requirements of its human and non-human participants.

4.5.4. LESSONS LEARNED

In this reflexive part of the discussion, we identify lessons regarding research methodology and outcomes, which we learned during the development of our Cyano-chromic Interface. We conclude with a set of recommendations that designers, operating at the intersection between design and biology, could consider and implement for designing living artefacts.

Addressing Balance Between Imaginaries And Scientific Grounding

Back and forth thinking between experiments and design conceptualization has been a common practice in material-driven and making practices in design and HCI [68][96], and more recently adopted by Bio-HCI (e.g., [5]). For our research, we had also adopted such an approach. On one hand, experiments helped us to better gauge the range of temporalities offered by the EC unit. Meanwhile, design thinking helped us to dig deeper into the semantics of our empirical findings in the context of the everyday. We suggest researchers, in case of technical hurdles, keep a holistic view on research goals which helps in better managing priorities given limited time of projects. We encourage the HCI community to explore and to strike a balance in the spectrum between epistemologically unlimited imaginaries and scientific grounding.

Tacit Knowledge in Biodesign

We had encountered a few protocols that required what some might call "tacit knowledge," a type of information or skill that is difficult to obtain or apply without first-hand experience. Although scientific literature can often provide step by step guides for certain experimental procedures, tacit knowledge, which may be critical in successful reproduction of a method, would not be obtained. For instance, when we were developing the cyano unit, we followed a published protocol, in which one of the steps had been omitted . We suspect that this may be due to the fact that its authors may perceive the step to be too trivial to be included in the publication. As we tried to replicate the published experiment and tailor it for our design, the protocol could not be reproduced; meaning that further time was spent on troubleshooting through trial and error, whilst attempting to obtain clarification directly from the protocol authors.

Reflecting on tacit knowledge not articulated by ourselves, we also found it difficult to describe all details of the making of our interface in this paper. This was most evident during the development of the EC unit. In particular, the screen printing technique required to imprint the electrochromic pigment was difficult to execute, by simply following its retailer's written instructions alone. It was only through a series of trial and error, and consultation with an experienced colleague that resolved the issue—a time consuming process that we could have anticipated, and a lesson that we invite others to learn from.

For this reason we propose that the HCI community should, 1) ensure transparency and repeatability when publishing research methods, and be more explicit on technical details when providing supplementary materials, 2) establish better communication channels between researchers, and 3) take extra care when connecting with potential collaborators. We also suggest HCI researchers establish strong collaborations with organism-specific experts at an early stage of the research, to ensure validity of methods and outcomes.

Strategising Lab And Studio Usage

We have found it efficient to strategise the use of two contrasting working environments: laboratory and "design studio" (in our case, a home studio), when working with living organisms. Designing and experimenting with microorganisms requires strict protocols and maintenance schedules (see, e.g., [15][5]). It often requires a biosafety level 1 biolab, which allows working with well-characterized agents which do not cause disease in humans. However, not all stages of the project need such regulated set-up. As the first author reflects on the start of the Cyano-chromic Interface journey; which involved living with and observing microbes outside of a lab. Here, using substitute laboratory resources suffice for culture maintenance (e.g., using glassware to replace laboratory flasks). Further still, a commercially accessible species of the cyanobacterium *Spirulina platensis* was chosen in place of *Synechocystis* sp. PCC 6803. In a similar way, we modified a 3D printer for bio-printing and custom-made a sterile cabin for the 3D printer at a prototyping workshop. With the commonly observed problem of limited lab access, we thus suggest designers to critically assess their particular requirements before constructing a plan of action, as a way to maximise efficiency of resource usage between the laboratory and the design studio. Furthermore, we suggest that more open approaches to understand and attune to microbes we design with, such as sensitizing with them from a first-person perspective at casual settings (e.g., home or design studio), are worth attention in the bio-HCI community. They could offer creative spaces for designers and researchers to engage with microbes in various ways and lead to rich and personal interpretations of microbial phenomena.

4.5.5. LIMITATIONS AND FUTURE WORK

Beyond Light and EC

Light has been explored for Cyano-chromic Interface as an environmental stimulus. However, we recognize that other factors, such as temperature and humidity, would also affect photosynthetic activity of the organism [97]. To that end, with this study, we could only scratch the surface of what could be done with Cyano-chromic Interface. However, focusing on one factor as a stimulus helps with technical implementation and provides initial insights for studying other factors. In our future work, we aim to explore the effects of other stimuli and other technologies for surfacing livingness (e.g., shape changing materials) and their interrelations to inspire other types of living interfaces in HCI. For example, using soft, flexible and transparent materials as surfacing technologies could enhance the life-like qualities of the interface towards more organic forms.

In-situ Explorations

We regard our interfaces as speculations towards generating potential imaginaries of how the Cyano-chromic Interface might be used in social and cultural contexts. We would like to further explore their care and performative potentials through empirical user studies that situate the interface in the everyday. This would require longitudinal studies (lasting between one to three months), which will present challenges of long-term maintenance of microbial viability. For example, we expect dehydration and increased risk of contamination during long-term operation of our interfaces—factors that also need careful management by the users. Furthermore, the interface might need to be presented with complementary guidelines to make this technology understandable by users. We aim to touch upon such practical challenges in our next iteration. To this end, despite its potential, questions of its performance in the wild are yet to be answered. Nevertheless, we are confident in the realization of these interfaces in future design iterations.

Instrumentalization and Moving forward

Instrumentalization can be an inevitable challenge in dealing with human-nonhuman relations [98] in biodesign. We recognize a certain level of instrumentalization

[98] of microbes in the Cyano-chromic Interface and proposed applications. For instance, habituating living cells in a hydrogel is an unnatural act that removes the microbes away from their natural environments. This could have consequences to their well-being that cannot yet be fully anticipated. To mitigate this tension, for our future research, exploring open and less "human-intended/intervened" interfaces could be considered as a starting point. One example of this is a concept named Flavo in Situ [22], which invites natural interactions of multiple organisms in a semi-natural habitat and an ecosystem. However, how such an open approach could be integrated in endeavours of temporal alignment is yet to be explored.

Sustainability of the Cyano-chromic Interface

Cyanobacteria are able to absorb carbon dioxide from the atmosphere and release oxygen, a process that is thought to contribute significantly to the global carbon cycle. However, designing an artificial habitat for them by default, is not necessarily climate-friendly. Experimenting and prototyping require products, chemicals, and materials that might not be sustainably produced, distributed, and disposed of. For instance, in our case, to harness the electrons from the organism, we used off-the-shelf conductive ink and electrical wires, which does not make the interface purely bio-based and regenerative. Lab experiments also generate a lot of disposables. Although one of the motivations behind microbial interfaces are for sustainability transition of the HCI field and ultimately the betterment of human-microbe relations, when it comes to practical implication of such interfaces, there is usually a trade-off between the desired effect and its environmental impact. Designers should be critical about the level of engineering involved to reach their goal. In our case, we reflect on our prototypes, whilst acknowledging that there is substantial room to analyse and to potentially improve on the environmental impact of the design, which is one of our future research endeavours.

4.6. CONCLUSION

This paper introduces *Cyano-chromic Interface*, designed to address the challenge of temporal dissonance between humans and microbes in living artefacts. Consisting of cyanobacteria and an electrochromic (EC) material, the interface helps to timely surface photosynthetic activity of the microbe. Grounding through a technical study of the interface performance, we illustrated its design primitives, which further inspired the development of application concepts. Through this we instantiate how the interface can be tuned for diverse functional and experiential outcomes in living artefacts; for instance, towards eliciting timely care and inviting continual reflections. We invite the HCI community to further explore technologically-mediated designs for aligning multiple temporalities, towards fostering reciprocal relationships between humans, microbes, and beyond.

REFERENCES

[1] J. Zhou, R. Kim, Z. Doubrovski, J. Martins, E. Giaccardi, and E. Karana. "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/10.1145/3563657.3596132.

[2] R. Kim, P. Pataranutaporn, J. Forman, S. A. Lee, I. H. Riedel-Kruse, M. Alistar, E. S. Lazaro Vasquez, K. Vega, R. van Dierendonck, G. Gome, O. Zuckerman, A. Vujic, D. S. Kong, P. Maes, H. Ishii, M. Sra, and S. Poslad. "Microbe-HCI: Introduction and Directions for Growth". 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: 10.1145/3411763.3450408. URL: https://doi.org/10.1145/3411763.3450408.

[3] T. Merritt, F. Hamidi, M. Alistar, and M. DeMenezes. "Living media interfaces: a multi-perspective analysis of biological materials for interaction". In: *Digital Creativity* 31.1 (2020), pp. 1–21. ISSN: 17443806. DOI: 10.1080/14626268. 2019.1707231.

[4] B. Barati, E. Karana, S. Pont, and T. van Dortmont. "LIVING LIGHT INTERFACES — AN EXPLORATION OF BIOLUMINESCENCE AESTHETICS". In: *Designing Interactive Systems Conference 2021*. DIS '21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 1215–1229. ISBN: 9781450384766. DOI: 10.1145/3461778.3462038. URL: https://doi.org/10.1145/3461778.3462038.

[5] E. G. Groutars, C. C. Risseeuw, C. Ingham, R. Hamidjaja, W. S. Elkhuizen, S. C. Pont, and E. Karana. "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*. CHI '22. New Orleans, LA, USA: Association for Computing Machinery, 2022. ISBN: 9781450391573. DOI: 10.1145/3491102.3517713. URL: https://doi.org/10.1145/3491102.3517713.

[6] V. Manzella, C. Gaz, A. Vitaletti, E. Masi, L. Santopolo, S. Mancuso, D. Salazar, and J. J. de las Heras. "Plants as Sensing Devices: The PLEASED Experience". In: *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems*. SenSys '13. Roma, Italy: Association for Computing Machinery, 2013. ISBN: 9781450320276. DOI: 10.1145/2517351.2517403. URL: https://doi.org/10.1145/2517351.2517403.

[7] I. Poupyrev, P. Schoessler, J. Loh, and M. Sato. "Botanicus Interacticus: Interactive Plants Technology". In: *ACM SIGGRAPH 2012 Emerging Technologies*. SIGGRAPH '12. Los Angeles, California: Association for Computing Machinery, 2012. ISBN: 9781450316804. DOI: 10.1145/2343456.2343460. URL: https://doi.org/10.1145/2343456.2343460.

[8] A. D. Cheok, R. T. Kok, C. Tan, O. N. N. Fernando, T. Merritt, and J. Y. P. Sen. "Empathetic living media". In: *Proceedings of the Conference on Designing Interactive Systems:*

Processes, Practices, Methods, and Techniques, DIS. 2008. ISBN: 9781605580029. DOI: 10.1145/1394445.1394495.

[9] F. Hamidi and M. Baljko. “Rafigh: An Edible Living Media Installation”. In: *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction*. TEI ’14. Munich, Germany: Association for Computing Machinery, 2014, pp. 345–346. ISBN: 9781450326353. DOI: 10.1145/2540930. 2555209. URL: https://doi.org/10.1145/2540930.2555209.

[10] S. A. Lee, E. Bumbacher, A. M. Chung, N. Cira, B. Walker, J. Y. Park, B. Starr, P. Blikstein, and I. H. Riedel-Kruse. “Trap It! A Playful Human- Biology Interaction for a Museum Installation”. 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. 2593–2602. ISBN: 9781450331456. DOI: 10.1145/2702123.2702220. URL: https://doi.org/10.1145/2702123.2702220.

[11] M. Alistar and M. Pevere. “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.

[12] F. Hamidi, L. Stamato, L. Scheifele, R. C. V. Hammond, and S. N. Asgarali-Hoffman. “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/10.1145/3411764.3445408.

[13] R. Kim, S. Thomas, R. van Dierendonck, and S. Poslad. “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*. FDG ’18. Malmö, Sweden: Association for Computing Machinery, 2018. ISBN: 9781450365710. DOI: 10.1145/3235765.3235798. URL: https://doi.org/10.1145/3235765.3235798.

[14] A. T. Lam, J. Griffin, M. A. Loeun, N. J. Cira, S. A. Lee, and I. H. Riedel-Kruse. “Pac-Euglena: A Living Cellular Pac-Man Meets Virtual Ghosts”. In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI ’20. Honolulu, HI, USA: Association for Computing Machinery, 2020, pp. 1–13. ISBN: 9781450367080. DOI: 10.1145/3313831.3376378. URL: https://doi.org/10.1145/3313831.3376378.

[15] N. Ofer, F. Bell, and M. Alistar. “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.

[16] K. J. Locey and J. T. Lennon. “Scaling laws predict global microbial diversity”. In: *Proceedings of the National Academy of Sciences* 113.21 (2016), pp. 5970–5975. DOI: 10.1073/pnas.1521291113. URL: https://www.pnas.org/doi/abs/10.1073/pnas.1521291113.

[17] R. Cavicchioli, W. J. Ripple, K. N. Timmis, F. Azam, L. R. Bakken, M. Baylis, M. J. Behrenfeld, A. Boetius, P. W. Boyd, A. T. Classen, and et al. “Scientists’ warning to humanity: Microorganisms and climate change”. In: *Nature Reviews Microbiology* 17.9 (2019), pp. 569–586. DOI: 10.1038/s41579-019-0222-5.

[18] D. J. Haraway. The companion species manifesto: Dogs, people, and significant otherness. Vol. 1. Chicago, the United States: Prickly Paradigm Press Chicago, 2003.

[19] D. Haraway. “Companion species, mis-recognition, and queer worlding”. In: *Queering the non/human*. Surrey, United Kingdom: Ashgate Hampshire and Burlington, 2008, pp. xxiii–xxxvi.

[20] D. J. Haraway. Manifestly haraway. Vol. 37. Minneapolis: University of Minnesota Press, 2016.

[21] E. Karana, B. Barati, and E. Giaccardi. “Living Artefacts: Conceptualizing Livingness as a Material Quality in Everyday Artefacts.” In: *International Journal of Design* 14.3 (2020), pp. 37–53. URL: http://www.ijdesign.org/ index.php/IJDesign/article/view/3957/923.

[22] R. Kim, C. Risseeuw, E. G. Groutars, and E. Karana. “Surfacing Livingness in Microbial Displays: A Design Taxonomy for HCI”. 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 .3581417. URL: https: //doi.org/10.1145/3544548.3581417.

[23] T. Kaneko and S. Tabata. “Complete genome structure of the unicellular cyanobacterium Synechocystis sp. PCC6803”. In: *Plant and Cell Physiology* 38.11 (1997), pp. 1171–1176.

[24] A. Bekker, H. Holland, P.-L. Wang, D. Rumble Iii, H. Stein, J. Hannah, L. Coetzee, and N. Beukes. “Dating the rise of atmospheric oxygen”. In: *Nature* 427.6970 (2004), pp. 117–120.

[25] J. Löwgren. “Toward an articulation of interaction esthetics”. In: *New Review of Hypermedia and Multimedia* 15.2 (2009), pp. 129–146.

[26] C.-C. Huang and E. Stolterman. “Temporality in Interaction Design”. In: *Proceedings of the 2011 Conference on Designing Pleasurable Products and Interfaces*. DPPI ’11. Milano, Italy: Association for Computing Machinery, 2011. ISBN: 9781450312806. DOI: 10.1145/2347504.2347572. URL: https: //doi.org/10.1145/2347504.2347572.

[27] S. Lundgren. “Toying with Time: Considering Temporal Themes in Interactive Artifacts”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’13. Paris, France: Association for Computing Machinery, 2013, pp. 1639–1648. ISBN: 9781450318990. DOI: 10.1145/ 2470654.2466217. URL: https://doi.org/10.1145/2470654.2466217.

[28] P. Pataranutaporn, T. Ingalls, and E. Finn. “Biological HCI: Towards integrative interfaces between people, computer, and biological materials”. In: *Conference on Human Factors in Computing Systems Proceedings* 2018-April (2018), pp. 1–6. DOI:

10.1145/3170427.3188662.

[29] J. Zhou, B. Barati, E. Giaccardi, and E. Karana. “Habitabilities of living artefacts: A taxonomy of digital tools for biodesign”. In: *International Journal of Design* 16.2 (2022), pp. 57–73. DOI: 10.57698/v16i2.05. URL: https://doi.org/10.57698/v16i2.05.

[30] J. W. Schopf and B. M. Packer. “Early Archean (3.3-billion to 3.5-billion-year- old) microfossils from Warrawoona Group, Australia”. In: *Science* 237.4810 (1987), pp. 70–73.

[31] L. J. Stal. “Cyanobacterial Mats and Stromatolites”. In: *Ecology of Cyanobacteria II: Their Diversity in Space and Time*. Dordrecht: Springer Netherlands, 2012, pp. 65–125. ISBN: 978-94-007-3855-3. DOI: 10.1007/978-94-007-3855-3_4. URL: https://doi.org/10.1007/978-94-007-3855-3_4.

[32] G. C. Cannon, C. E. Bradburne, H. C. Aldrich, S. H. Baker, S. Heinhorst, and J. M. Shively. “Microcompartments in prokaryotes: carboxysomes and related polyhedra”. In: *Applied and environmental microbiology* 67.12 (2001), pp. 5351–5361.

[33] A. J. McCormick, P. Bombelli, A. M. Scott, A. J. Philips, A. G. Smith, A. C. Fisher, and C. J. Howe. “Photosynthetic biofilms in pure culture harness solar energy in a mediatorless bio-photovoltaic cell (BPV) system”. In: *Energy & Environmental Science* 4.11 (2011), pp. 4699–4709.

[34] A. J. McCormick, P. Bombelli, R. W. Bradley, R. Thorne, T. Wenzel, and C. J. Howe. “Biophotovoltaics: oxygenic photosynthetic organisms in the world of bioelectrochemical systems”. In: *Energy & Environmental Science* 8.4 (2015), pp. 1092–1109.

[35] L. T. Wey, P. Bombelli, X. Chen, J. M. Lawrence, C. M. Rabideau, S. J. Rowden, J. Z. Zhang, and C. J. Howe. “The development of biophotovoltaic systems for power generation and biological analysis”. In: *ChemElectroChem* 6.21 (2019), pp. 5375–5386.

[36] M. Sawa, A. Fantuzzi, P. Bombelli, C. J. Howe, K. Hellgardt, and P. J. Nixon. “Electricity generation from digitally printed cyanobacteria”. In: *Nature communications* 8.1 (2017), pp. 1–10.

[37] E. Frier and J. Douenias. Living Things. Frier and Douenias. 2015. URL: http://www.ethanfrier.com/living-things.

[38] ecologicStudio. AirBubble by ecoLogiStudio for Otrivin Breathe Clean. ecologicStudio. 2021.URL:https://www.ecologicstudio.com/projects/airbubble-playground-and-exhibition.

[39] R. Aghighi. Biogarmentry: Photosynthetic Living textile for an alternative everyday. Material Incubator. n.d. URL: https://www.materialincubator. com/biogarmentry.

[40] J. Hahn. Bio-ID Lab designs DIY algae-infused tiles that can extract toxic dyes from water. Dezeen. 2019. URL: https://www.dezeen.com/2019/09/21/bio- id-lab-indus-algae-tiles-water/.

[41] L. Giraud. Installation Algaegraphique. Giraud. 2014. URL: http://www. liagiraud. com/cultures/.

[42] J. Dabrowski and E. V. Munson. “40 years of searching for the best computer system response time”. In: Interacting with Computers 23.5 (2011), pp. 555–564.

[43] H. Ishii and B. Ullmer. “Tangible bits: towards seamless interfaces between people, bits and atoms”. In: *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*. 1997, pp. 234–241.

[44] L. Hallnäs and J. Redström. “Slow Technology – Designing for Reflection”. In: *Personal Ubiquitous Comput*. 5.3 (Jan. 2001), pp. 201–212. ISSN: 1617-4909. DOI: 10.1007/PL00000019. URL: https://doi.org/10.1007/PL00000019.

[45] W. Odom, R. Banks, A. Durrant, D. Kirk, and J. Pierce. “Slow Technology: Critical Reflection and Future Directions”. In: *Proceedings of the Designing Interactive Systems Conference*. DIS ’12. Newcastle Upon Tyne, United Kingdom: Association for Computing Machinery, 2012, pp. 816–817. ISBN: 9781450312103. DOI: 10 .1145 /2317956 .2318088. URL: https: //doi.org/10.1145/2317956.2318088.

[46] A. Parkes and C. Dickie. “A Biological Imperative for Interaction Design”. In: *CHI ’13 Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’13. Paris, France: Association for Computing Machinery, 2013, pp. 2209–2218. ISBN: 9781450319522. DOI: 10.1145/2468356.2468742. URL: https://doi.org/10.1145/2468356.2468742.

[47] D. Lockton, D. Ricketts, S. Aditya Chowdhury, and C. H. Lee. “Exploring Qualitative Displays and Interfaces”. In: *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’17. Denver, Colorado, USA: Association for Computing Machinery, 2017, pp. 1844–1852. ISBN: 9781450346566. DOI: 10.1145/3027063.3053165. URL: https://doi.org/10.1145/3027063.3053165.

[48] A. Desjardins, J. McWhirter, J. Petelka, C. Simon, Y. Shin, R. K. Peven, and P. Widjaja. “On the Making of Alternative Data Encounters: The Odd Interpreters”. 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: 10.1145/3544548.3581323. URL: https://doi.org/10.1145/3544548.3581323.

[49] J. Cheng, A. Bapat, G. Thomas, K. Tse, N. Nawathe, J. Crockett, and G. Leshed. “GoSlow: Designing for Slowness, Reflection and Solitude”. In: *CHI ’11 Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’11. Vancouver, BC, Canada: Association for Computing Machinery, 2011, pp. 429–438. ISBN: 9781450302685. DOI: 10.1145/1979742.1979622. URL: https://doi.org/10.1145/1979742.1979622.

[50] G. Leshed. “Slowing down with personal productivity tools”. In: *Interactions* 19.1 (2012), pp. 58–63.

[51] W. T. Odom, A. J. Sellen, R. Banks, D. S. Kirk, T. Regan, M. Selby, J. L. Forlizzi, and J. Zimmerman. “Designing for Slowness, Anticipation and Re-Visitation: A Long Term Field Study of the Photobox”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’14. Toronto, Ontario, Canada: Association for Computing Machinery, 2014, pp. 1961–1970. ISBN: 9781450324731. DOI: 10.1145/2556288.2557178. URL: https://doi.org/10.1145/2556288.2557178.

[52] W. Odom, R. Wakkary, I. Bertran, M. Harkness, G. Hertz, J. Hol, H. Lin, B. Naus, P. Tan, and P. Verburg. “Attending to Slowness and Temporality with Olly and Slow Game: A Design Inquiry Into Supporting Longer- Term Relations with Everyday Computational Objects”. 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: 10.1145/3173574.3173651. URL: https://doi.org/10.1145/3173574.3173651.

[53] L. Pschetz and M. Bastian. “Temporal Design: Rethinking time in design”. In: *Design Studies* 56 (2018), pp. 169–184.

[54] P. Pataranutaporn, A. Vujic, D. S. Kong, P. Maes, and M. Sra. “Living Bits: Opportunities and Challenges for Integrating Living Microorganisms in Human-Computer Interaction”. In: *Proceedings of the Augmented Humans International Conference*. AHs ’20. Kaiserslautern, Germany: Association for Computing Machinery, 2020. ISBN: 9781450376037. DOI: 10.1145/3384657. 3384783. URL: https://doi.org/10.1145/3384657.3384783.

[55] S. Kuznetsov, A. S. Taylor, T. Regan, N. Villar, and E. Paulos. “At the Seams: DIYbio and Opportunities for HCI”. In: *Proceedings of the Designing Interactive Systems Conference*. DIS ’12. Newcastle Upon Tyne, United Kingdom: Association for Computing Machinery, 2012, pp. 258–267. ISBN: 9781450312103. DOI: 10.1145/2317956.2317997. URL: https://doi.org/10.1145/2317956.2317997.

[56] S. Kuznetsov, W. Harrigan-Anderson, H. Faste, S. E. Hudson, and E. Paulos. “Community Engagements with Living Sensing Systems”. In: *Proceedings of the 9th ACM Conference on Creativity & Cognition*. C&C ’13. Sydney, Australia: Association for Computing Machinery, 2013, pp. 213–222. ISBN: 9781450321501. DOI: 10.1145/2466627.2466638. URL: https://doi.org/10.1145/2466627.2466638.

[57] F. Bell, N. Ofer, E. Frier, E. McQuaid, H. Choi, and M. Alistar. “Biomaterial Playground: Engaging with Bio-Based Materiality”. In: *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI EA ’22. New Orleans, LA, USA: Association for Computing Machinery, 2022. ISBN: 9781450391566. DOI: 10.1145/3491101.3519875.

URL: https://doi.org/10.1145/3491101.3519875.

[58] R. Kim, S. Thomas, R. van Dierendonck, N. Bryan-Kinns, and S. Poslad. “Working with Nature’s Lag: Initial Design Lessons for Slow Biotic Games”. In: *International Conference on the Foundations of Digital Games*. FDG ’20. Bugibba, Malta: Association for Computing Machinery, 2020. ISBN: 9781450388078. DOI: 10.1145/3402942.3409790. URL: https://doi.org/10.1145/3402942.3409790.

[59] H. Kim, L. C. Gerber, D. Chiu, S. A. Lee, N. J. Cira, S. Y. Xia, and I. H. Riedel-Kruse. “LudusScope: accessible interactive smartphone microscopy for life-science education”. In: *PloS one* 11.10 (2016), e0162602.

[60] L. C. Gerber, H. Kim, and I. H. Riedel-Kruse. “Interactive Biotechnology: Design Rules for Integrating Biological Matter into Digital Games.” In: *DiGRA/FDG* 13.1 (2016), p. 16.

[61] M. Chang, C. Shen, A. Maheshwari, A. Danielescu, and L. Yao. “Patterns and Op-

portunities for the Design of Human-Plant Interaction”. In: *Designing Interactive Systems Conference*. DIS ’22. Virtual Event, Australia: Association for Computing Machinery, 2022, pp. 925–948. ISBN: 9781450393584. DOI: 10.1145/3532106.3533555. URL: https://doi.org/10.1145/3532106. 3533555.

[62] H. Steiner, P. Johns, A. Roseway, C. Quirk, S. Gupta, and J. Lester. “Project Florence: A Plant to Human Experience”. In: *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’17. Denver, Colorado, USA: Association for Computing Machinery, 2017, pp. 1415–1420. ISBN: 9781450346566. DOI: 10.1145/3027063.3052550. URL: https://doi.org/10.1145/3027063.3052550.

[63] S. Tao, Y. Huang, and A. Lioret. “Plant Interaction”. In: *Proceedings of the 2016 Virtual Reality International Conference*. VRIC ’16. Laval, France: Association for Computing Machinery, 2016. ISBN: 9781450341806. DOI: 10.1145/ 2927929.2927954. URL: https://doi.org/10.1145/2927929.2927954.

[64] D. Briscoe. “Living Wall: Digital Design and Implementation”. In: *Journal of Digital Landscape Architecture* 5 (June 2020), pp. 646–653. DOI: 10.14627/537690066. URL: https://doi.org/10.14627/537690066.

[65] D. Easterly, M. Kenyon, and T. Rorke. “Tardigotchi: Considerations on Pets and Digital Simulations”. In: *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction.* TEI ’11. Easterly. Funchal, Portugal: Association for Computing Machinery, 2010, pp. 391–392. ISBN: 9781450304788. DOI: 10.1145/1935701.1935795. URL: https://doi.org/10.1145/1935701.1935795.

[66] D. Chen, Y. a. Seong, H. Ogura, Y. Mitani, N. Sekiya, and K. Moriya. “Nukabot: Design of Care for Human-Microbe Relationships”. 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: 10.1145/3411763.3451605. URL: https: //doi.org/10.1145/3411763.3451605.

[67] R. Armstrong. “Biodesign for a culture of life: Of microbes, ethics, and design”. In: *Lockton, D., Lenzi, S., Hekkert, P., Oak, A., Sádaba, J., Lloyd, P. (eds.) Spain: DRS2022: Bilbao*, 2022, pp. 1–20. DOI: 10.21606/drs.2022.144. URL: https://doi.org/10.21606/drs.2022.144.

[68] E. Karana, B. Barati, V. Rognoli, A. Zeeuw Van Der Laan, et al. “Material driven design (MDD): A method to design for material experiences”. In: *International Journal of Design* 9.2 (2015), pp. 35–54.

[69] M. H. Chua, T. Tang, K. H. Ong, W. T. Neo, and J. W. Xu. “Introduction to Electrochromism”. In: *Electrochromic Smart Materials: Fabrication and Applications*. Croydon, UK: The Royal Society of Chemistry, Jan. 2019. ISBN: 978-1-78801-143-3. DOI: 10.1039/9781788016667-00001. URL: https: //doi.org/10.1039/9781788016667-00001.

[70] W. Jensen, M. Löchtefeld, and H. Knoche. “ShadowLamp: An Ambient Display with Controllable Shadow Projection Using Electrochromic Materials.” In: *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI EA ’19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–6. ISBN: 9781450359719.

DOI: 10.1145/ 3290607.3313011. URL: https://doi.org/10.1145/3290607.3313011.

[71] E. M. Spiesz, K. Yu, B. A. Lehner, D. T. Schmieden, M.-E. Aubin-Tam, and A. S. Meyer. "Three-dimensional Patterning of Engineered Biofilms with a Do-it-yourself Bioprinter". In: *JoVE (Journal of Visualized Experiments)* 147 (2019), e59477.

[72] B. E. Logan, M. J. Wallack, K.-Y. Kim, W. He, Y. Feng, and P. E. Saikaly. "Assessment of microbial fuel cell configurations and power densities". In: *Environmental Science & Technology Letters* 2.8 (2015), pp. 206–214.

[73] D. K. Rosner, M. Ikemiya, D. Kim, and K. Koch. "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.

[74] S. E. Cohen and S. S. Golden. "Circadian rhythms in cyanobacteria". In: *Microbiology and Molecular Biology Reviews* 79.4 (2015), pp. 373–385.

[75] A. L. Tsing. The mushroom at the end of the world: On the possibility of life in capitalist ruins. Princeton University Press, 2015.

[76] J. Liu, D. Byrne, and L. Devendorf. "Design for collaborative survival: An inquiry into human-fungi relationships". In: *Conference on Human Factors in Computing Systems - Proceedings* 2018-April (2018). DOI: 10.1145/3173574.3173614.

[77] M. P. de la Bellacasa. *Matters of Care: Speculative Ethics in More than Human Worlds.* Minneapolis: University of Minnesota Press, 2017. ISBN: 9781517900656. URL: http://www.jstor.org/stable/10.5749/j. ctt1mmfspt (visited on 05/17/2023).

[78] F. Aspling, J. Wang, and O. Juhlin. "Plant-computer interaction, beauty and dissemination". In: *ACM International Conference Proceeding Series* 15-17-Nove (2016). DOI: 10.1145/2995257.2995393.

[79] E. Karana, E. Giaccardi, and V. Rognoli. "Materially yours". In: *Routledge Handbook of Sustainable Product Design*. London: Routledge, 2017, pp. 206– 221.

[80] A. Vallgårda and J. Redström. "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.

[81] C. Zheng, P. Gyory, and E. Y.-L. Do. "Tangible Interfaces with Printed Paper Markers". In: *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. DIS '20. Eindhoven, Netherlands: Association for Computing Machinery, 2020, pp. 909–923. ISBN: 9781450369749. DOI: 10.1145/3357236. 3395578. URL: https://doi.org/10.1145/3357236.3395578.

[82] G. Wang, T. Cheng, Y. Do, H. Yang, Y. Tao, J. Gu, B. An, and L. Yao. "Printed Paper Actuator: A Low-Cost Reversible Actuation and Sensing Method for Shape Changing Interfaces". 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: 10.1145/3173574.3174143. URL: https://doi.org/10.1145/3173574.3174143.

[83] H. Oh, T. D. Ta, R. Suzuki, M. D. Gross, Y. Kawahara, and L. Yao. “PEP (3D Printed Electronic Papercrafts): An Integrated Approach for 3D Sculpting Paper-Based Electronic Devices”. 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: 10.1145/3173574.3174015. URL: https://doi.org/10.1145/3173574.3174015.

[84] J. M. Dauner, M. E. Karagozler, and I. Poupyrev. “Paper Generators: Harvesting Energy from Touching, Rubbing and Sliding”. In: *CHI ’14 Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’14. Toronto, Ontario, Canada: Association for Computing Machinery, 2014, pp. 161–162. ISBN: 9781450324748. DOI: 10.1145/2559206.2579480. URL: https://doi.org/10.1145/2559206.2579480.

[85] D. A. Mellis, S. Jacoby, L. Buechley, H. Perner-Wilson, and J. Qi. “Microcontrollers as Material: Crafting Circuits with Paper, Conductive Ink, Electronic Components, and an "Untoolkit"”. In: *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*. TEI ’13. Barcelona, Spain: Association for Computing Machinery, 2013, pp. 83–90. ISBN: 9781450318983. DOI: 10.1145/2460625.2460638. URL: https://doi.org/10.1145/2460625.2460638.

[86] E. Giaccardi and E. Karana. “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.

[87] E. Karana, E. Giaccardi, N. Stamhuis, and J. Goossensen. “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 Coing Machinery, 2016, pp. 619–631. ISBN: 9781450340311. DOI: 10.1145/2901790.2901909. URL: https://doi.org/10.1145/2901790.2901909.

[88] Y. Kinoshita, K. Go, R. Kozono, and K. Kaneko. “Origami Tessellation Display: Interaction Techniques Using Origami-Based Deformable Surfaces”. In: *CHI ’14 Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’14. Toronto, Ontario, Canada: Association for Computing Machinery, 2014, pp. 1837–1842. ISBN: 9781450324748. DOI: 10.1145/2559206.2581172. URL: https://doi.org/10.1145/2559206.2581172.

[89] D. Lee, K. Saito, T. Umedachi, T. D. Ta, and Y. Kawahara. “Origami Robots with Flexible Printed Circuit Sheets”. In: *Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers*. UbiComp ’18. Singapore, Singapore: Association for Computing Machinery, 2018, pp. 392–395. ISBN: 9781450359665. DOI: 10.1145/3267305.3267620. URL: https://doi.org/10.1145/3267305.3267620.

[90] L. Sun, J. Li, M. Li, Y. Fan, Y. Chen, D. Pan, Y. Yang, J. Ji, Y. Tao, and G. Wang. “3DP-Ori:

Bridging-Printing Based Origami Fabrication Method with Modifiable Haptic Properties". In: *Adjunct Proceedings of the 34th Annual ACM Symposium on User Interface Software and Technology*. UIST '21 Adjunct. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 74–77. ISBN: 9781450386555. DOI: 10.1145/3474349.3480233. URL: https://doi.org/10.1145/3474349.3480233.

[91] M. H. Kaspersen, S. Hines, M. Moore, M. K. Rasmussen, and M. A. Dias. "Lifting Kirigami Actuators Up Where They Belong: Possibilities for SCI". In: *Proceedings of the 2019 on Designing Interactive Systems Conference*. DIS '19. San Diego, CA, USA: Association for Computing Machinery, 2019, pp. 935–947. ISBN: 9781450358507. DOI: 10.1145/3322276.3323688. URL: https://doi.org/10.1145/3322276.3323688.

[92] C. Jiang, F. Rist, H. Pottmann, and J. Wallner. "Freeform Quad-Based Kirigami". In: *ACM Trans. Graph*. 39.6 (Nov. 2020). ISSN: 0730-0301. DOI: 10.1145/ 3414685.3417844. URL: https://doi.org/10.1145/3414685.3417844.

[93] C. Zheng, H. Oh, L. Devendorf, and E. Y.-L. Do. "Sensing Kirigami". In: *Proceedings of the 2019 on Designing Interactive Systems Conference*. DIS '19. San Diego, CA, USA: Association for Computing Machinery, 2019, pp. 921–934. ISBN: 9781450358507. DOI: 10.1145/3322276.3323689. URL: https://doi.org/10.1145/3322276.3323689.

[94] R. S. H. Smith, C. Bader, S. Sharma, D. Kolb, T.-C. Tang, A. Hosny, F. Moser, J. C. Weaver, C. A. Voigt, and N. Oxman. "Hybrid Living Materials: Digital Design and Fabrication of 3D Multimaterial Structures with Programmable Biohybrid Surfaces". In: *Advanced Functional Materials* 30.7 (2020), p. 1907401.

[95] H. Mor, T. Yu, K. Nakagaki, B. H. Miller, Y. Jia, and H. Ishii. "Venous Materials: Towards Interactive Fluidic Mechanisms". In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI '20. Honolulu, HI, USA: Association for Computing Machinery, 2020, pp. 1–14. ISBN: 9781450367080. DOI: 10.1145/3313831.3376129. URL: https://doi.org/10.1145/3313831.3376129.

[96] L. Devendorf and K. Ryokai. "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.

[97] A. Konopka and T. D. Brock. "Effect of temperature on blue-green algae (cyanobacteria) in Lake Mendota". In: *Applied and Environmental Microbiology* 36.4 (1978), pp. 572–576.

[98] M. Livio and L. Devendorf. "The Eco-Technical Interface: Attuning to the Instrumental". 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: 10.1145/3491102.3501851. URL: https://doi.org/10.1145/3491102.3501851.

5 Design Experiment II Caring for Microbes in Everyday Life

“The notion of 'matters of care' is a proposition to think with: rather than indicating a method to 'unveil' what matters of fact are, it suggests that we engage with them so that they generate more caring relationalities.”

—Maria Puig de la Bellacasa

This chapter delves into the second design experiment that explores the role of materiality in facilitating the creative unfolding of care practices in everyday settings. In this chapter, a cyanobacterial living artefact with air-purifying capabilities was designed, and eight participants were invited to live with it over a two-week period. The artefact's versatility, enabled by its color-changing, pliable, adhesive, and suspendable properties, allowed participants to place it in various locations within their domestic spaces, based on their assessment of where air purification was needed and where lighting conditions would support the artefact's vitality. Visual documentation and semi-structured interviews were conducted to capture the participants' experiences with the artefact. The findings reveal distinct roles of materiality in shaping care practices, particularly in relation to labor, knowledge, and exploration. Additionally, the study highlights the complex design space that involves considerations of openness, temporalities, and semantic fitness, all of which contribute to fostering mutualistic care in human-microbe interactions in living artefacts.

This chapter was originally published in the Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems; as such, references to "this paper" pertain to that publication. CHI is a leading annual venue where diverse communities across design, interaction, biological HCI, critical HCI, and sustainable and ecological HCI converge to share research advances—including those exploring how to design with living systems. Within this context, ongoing discussions have emerged around care for more-than-human beings in both design and design-oriented HCI. This chapter contributes to these conversations by offering a novel materiality-led approach to designing care interactions with microbes, situated within and mediated through living artefacts.

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5.1. INTRODUCTION

Care is omnipresent in everyday human life, and extends its reach to encompass more-than-human worlds [2]. As humans, we care and are cared for, within human realms [3, 4]. But also beyond it: in reciprocal and evolving relationships with other-than-human "companion species" [5], with plants [6, 7], animals [8–11], microbial "workhorses" [12] and our human microbiome [13].

The concept of care for microorganisms has recently gained increasing attention across design and Human-Computer Interaction (HCI). In recognition of microbes' significance, especially of its abundance and diversity [14] and impact on the Earth's climate [15], emerging special interest groups (e.g., microbe-HCI [16]) and microbial interfaces [17–21] challenge existing forms of human-microbe relations. For example, scholars have generated discourse around empathy [22], more-than-human temporalities [21, 23, 24], noticing [21, 25, 26], and care [12, 26, 27], towards reciprocal and evolving relationships with microorganisms involved in living artefacts [28].

To address the challenges of temporality and scale associated with caring for microbes [23], HCI researchers have previously proposed diverse digital technological applications [12, 26]. Yet, the care actions expected from the human co-habitants of these living artefacts were predetermined by the designers. As such, it hinders the organic emergence of creative configurations for care actions in everyday life, making them difficult, if not impossible, to develop spontaneously. This could especially impede the seamless integration of these artefacts into our everyday lives, thereby affecting the sense of cohabitation and coevolution with other-than-human entities. To this end, we see great potential of materiality in facilitating the creative unfolding of care practices. Specifically, we are intrigued by the temporal and performative qualities of materials [29, 30] and the potential role of these qualities in the emergence of novel caregiving practices in the every day, while building intricate and dynamic relationships with living artefacts.

To explore this premise, we designed a *living cyanobacteria artefact*, giving particular emphasis to its temporal and performative material qualities. We then conducted an in-situ longitudinal study with eight participants, who cohabited with the living artefact over two weeks.

5.1.1. CONTRIBUTIONS

By engaging with individuals who possess a wide spectrum of caregiving experiences towards other-than-human living beings, our study delves into the crucial role of materiality in nurturing care practices in everyday life. This exploration not only sheds light on the significance of materiality but also uncovers its potential to serve as a powerful catalyst for HCI designers aiming to cultivate creative care approaches specifically tailored to microbial living artefacts.

Given the relatively nascent nature of biological integration in design and its associated technical and practical challenges, there is a lack of longitudinal studies involving living artefacts. It requires the design of a reliable living artefact that participants can live and interact with over an extended period, this includes challenges of maintaining the organisms' vitality and ensuring adequate levels of safety for people who may interact with them. To that end, with the design of our living artefact, we strive to inspire HCI researchers, encouraging the development of innovative living artefact designs conducive to field studies. Furthermore, to our knowledge, our work represents a first longitudinal in-situ study involving cyanobacteria-based living artefacts. Our research offers insights into distinct temporal patterns and behaviours exhibited by these microbes within domestic settings, framed to offer useful guidance for HCI designers. Moreover, we showcase a potential method for designing habitats tailored to accommodate these organisms. Additionally, no existing studies to date have specifically centred on materiality and its capacity to foster care practices for living artefacts. In this context, we offer our initial insights into how temporal and performative qualities of living artefacts could be meticulously designed and fine-tuned to elicit and shape novel care practices in everyday life.

5.2. RELATED WORKS

5.2.1. SOCIAL DIMENSIONS OF MICROBIAL LIVING ARTEFACTS

Our paper positions "care" within the context of microbial living artefacts as an initial exploration into human-microbe relationships that could potentially integrate into our daily practices. We have been actively engaging and collaborating with microbes in diverse life activities, harnessing their distinct abilities, notably in practices such as beer brewing, sourdough baking, and medicine production. In recent decades, scholars in design and HCI fields have broadened the scope of human-microbe relations to encompass more diverse organisms and contexts, such as shared environment sensing and display [13, 18, 19, 31], direct interactions [20], biotic games [32] and interactive public arts [33].

With novel functions and experiences endowed by microbes, these endeavours have sparked imaginations of alternative social interactions with other-than-humans, driven by an aspiration to enhance our planet's sustainability and harmonious relationships between species. More profoundly, they have triggered meaningful dialogues within design and HCI on new epistemological perspectives, associated challenges and opportunities that arise when designing and living with microbial artefacts. Besides our long-existing understanding that living media could naturally promote human empathy [22], they might also bring about an experience of shared "vitality" [17] which could lead to motivations of caring. Delving deeper into this social dimension of living artefacts, Karana et al. [28] proposed three fundamental design principles to facilitate living artefacts to be deeply embedded within everyday life: *mutualistic care, living aesthetics and habitabilities*. These design principles call upon designers to understand and embrace diverse temporalities of living beings, and to nurture reciprocal relations and sensibilities of habitat relationalities with them. Additionally, design strategies, as proposed by Kim et al. [23], enable the surfacing of the livingness of microbes, as a way to overcome and manage challenges in human perceptions of the distinct temporalities, scales, and semantics of the microbial world. In line with this approach, Zhou et al. [21] proposed microbial interfaces and artefacts that align human-microbe temporal dissonance, fostering imaginaries of alternative reciprocal human-microbe relations. Our work endeavours to contribute to the ongoing discourse on the social dimensions of living artefacts by exploring how we can design for care. We collaborate with a cyanobacterium (*Synechocystis* sp. PCC6803), a microorganism that presents unique temporality that poses challenges for timely care [21].

Cyanobacteria Artefacts in Design and HCI

Commonly known as "blue-green algae," cyanobacteria are a type of bacteria that distinguishes itself from other bacterial species through its ability to perform photosynthesis, a biological process shared with green algae and green-leafed plants. Amongst photosynthetic species, microalgae and cyanobacteria are microbial species that have been integrated into design and HCI projects. These projects encompass a range of innovations, such as an energy-converting living light system [34], an interactive air-purifying playground [35], air-purifying garments [36], outdoor water-detoxing tiles [37], light-responsive image displays [38], electricity-producing wallpaper [39], and temporal-aligning interfaces and artefacts [21]. Leveraging their photosynthetic process, cyanobacteria can metabolise using only light, water, carbon dioxide, and various inorganic substances. To sustain themselves, they continually absorb sunlight and carbon dioxide while releasing oxygen into the atmosphere—a process known as carbon fixation, which plays a significant role in the global carbon cycle [40]. Cyanobacteria's capacity for carbon capture and oxygen generation has been demonstrated in living material designs [41–44]. When exposed to light, these microorganisms accumulate green biomass over time, typically spanning days to weeks, thereby transforming the total absorbed light into green living colours [21].

Whilst most existing works have explored the functional potential of photosynthetic microbes, e.g., purifying air, Zhou et al. [21] have called attention to their unique temporality and the challenges they pose to timely human care. They instantiated how the alignment of human-cyanobacteria temporalities could foster new reciprocal human-microbe relations, by creating a tangible interface with cyanobacteria facilitating human noticing of the microbe's well-being and envisioning mutualistic care enabled through the interface. Building on this work, we further explore care in situ for a potential air-purifying living artefact designed with cyanobacterium *Synechocystis* sp. PCC6803.

5.2.2. CARE FOR OTHER-THAN-HUMANS IN HCI

Care as "everything we do to maintain, continue and repair 'our world' so that we can live in it as well as possible" [45] is of vital importance in our current times of ecological crisis. Through practising care for ourselves and those around us, we aim to nurture not only our own lives but also other-than-human cohabitants that share the environment with us through intricate relations, dependencies and entanglements. Care involves not only mundane labour and affection but also higher ethical and political concerns [2]. Moreover, it is essential to also recognize that care is not always positive and fulfilling; embracing the values of discomfort that care might involve can also be unsettling [46]. Care inherently involves tensions, yet these can be desirable and generative when approached through a design perspective [3].

In the call to pursue alternatives for the long-existing destructive industrial paradigm, HCI researchers have been turning to feminist care ethics and posthumanism, and exploring care possibilities both theoretically and in practice. In HCI, caring for more-than-human and not-just-human [47] concerns moving away from anthropocentrism and functionalism [48] and convening "constituency" of humans and non-humans as matters of care before any design is committed [49]. Care for other-than-human beings is a relational, embodied, and ongoing practice that is necessarily particular [47]. Pioneering researchers committed to care-ful HCI have offered us valuable insights to design care for diverse other-than-humans. Some examples include care imaginaries towards home IoT [50], tensions in care for loved ones [3], design exploration for tactful feminist care [4], care-ful practices and artefacts initiated by local communities in farming [48], attention to animal welfare [8], and ethics of care when working with microbes [12]. In parallel, the notion of *mutualistic care* [28] has been introduced in the biodesign framework of *living artefacts*, suggesting the reciprocity and evolving nature of care between humans and living organisms in the artefacts. We are eager to delve deeper into this notion of care in our research.

Care concerning specifically other-than-human living beings such as microorganisms has been a topic of interest that has gathered traction amongst artists, designers and HCI researchers (e.g., [12, 20, 21, 23, 25–27, 31, 51]). Here, we briefly discuss different ways in which care for microbes has been studied in HCI, to help us further distinguish our contribution. In *Tardigotchi* [51], a water bear's wellbeing is displayed as a digital avatar on a pixelated display and also made observable through a microscope on the artefact. Through digital reminders of the water bear being hungry or satisfied, people can perform feeding actions for the microbe accordingly. Similarly, *Nukabot* [26] is an artefact that communicates progress and the well-being of food-fermenting bacteria through digital mediation and cultural referencing that emotionally appeal to the humans who live with the artefact, to care for, and to manually stir the fermenting bran at appropriate times. Contrastingly, designers of *Rafigh* [31], utilize unprocessed visible aesthetics of mushroom growth, to appeal to its users to become engaged with the care practices involving speech learning and watering of the mushrooms.

Amongst these works, some have demonstrated how in-situ longitudinal studies around care for living organisms could be approached [26, 27, 31]. Chen et al.'s [26] artefact design revolved around familiar organisms and established care practices; [31] and [27] investigated how physical care towards a living organism influences human relationship with familiar products. However, none of the works have studied the role of materiality of living artefacts in nurturing diverse care practices over time. In these works, to elicit care actions, there is usually a set of input-output (I/O) rules in the artefact that links one specific action (e.g., stirring in Nukabot) or a targeted behaviour change (e.g., speech learning in Rafigh) to a microbial need. Yet, caregiving interactions are often prescribed by the artefacts' designers. This makes it difficult (if not impossible) for creative configurations related to care actions to emerge organically in the everyday. To delve into this particular aspect of care within the frame of designing a living artefact, we turn our attention to materiality, more specifically, the performative qualities of materials that can be harnessed in the design of the artefact.

5.2.3. MATERIALITY AND PERFORMATIVITY OF MATERIALS IN HCI

Over the past decade, HCI scholars have persistently turned away from the view of the material world as passive and inert. They now share the common understanding that materiality, intended here as the material qualities of artefacts, plays an active role in the unfolding of dynamic relationships between people and interactive systems [52–56], offering new interaction possibilities and experiences that are intimately entangled with social practices [29].

Giaccardi and Karana [29] called for HCI designers to pay attention to the performative qualities of materials, referring to their active role in shaping our peculiar ways of doing, and ultimately, daily practices. Building on this, Karana et al. [30] presented designerly explorations of how the performative qualities of materials can invite novel ways of unfolding a social practice (in this case, the mundane activity of "tuning the radio"). To guide designers in harnessing performativity of smart materials, Barati et al. [57] offer a framework for material design process to prompt specific actions from people. In a similar vein, by examining lived experiences with a deformable lampshade, Zhong et al. [58] revealed that "deformability" of the artefact can stimulate participants' creativity in their interactions with it, such as "drawing on the artefact."

In line with these studies, we argue that materiality, especially the performative qualities of materials, holds the potential to facilitate the creative unfolding of care practices. The importance of creativity in care has been underscored in *Matters of Care* [2]. It emphasises uneventful everyday occurrences as transformative, and advocates for "improvisational haptic creativity" for humans to engage with more-than-human care, as a way to disrupt the dominant anthropocentric view of innovation ([2], p.214). In line with this call, we propose that performative qualities of materials [29] can support exploratory care practices towards living artefacts. In the experience of materials, performances are carried out and altered in the development of practice through recurring encounters with the materials [29]. In this dynamic, materials are not static; they change as a result of these performances, potentially influencing how performances further develop. Embracing the concept of materials experience in our design allows for the adaptability of living artefacts across a broader spectrum of social situations. It also opens up avenues for what could be framed as creative alternatives [59], co-performance [60] and multiplicity [49], both with and through living artefacts.

In the design of our artefact, to enhance its potential to allow for the creative unfolding of everyday care practices, we paid special attention to the artefact's temporal and performative qualities, considering both its living and nonliving components. In particular, we focused on the temporal colour changes expressed by the living cyanobacteria, along with qualities such as softness, transparency, flexibility, and stickability of the nonliving components. The form (shape and size) has also been taken into account in the final design of the artefact.

5.3. METHODOLOGY

We undertook a research through design (RtD) process, through which we used the research artefact as a catalyst and carrier for discourse [61]. Accordingly, the process was structured into two key phases: the design of a "living cyanobacteria artefact," and a two-week in-situ study to comprehend the real-life experiences associated with caring for this artefact. In the design of the artefact, we drew from the Material Driven Design method [62], particularly from material tinkering [63] and the making/tuning of performativity [30, 57] techniques, to explore suitable materials for the artefact, and to understand performativity of the selected material. Notably, prior to the work presented in this paper, the first author had lived and designed with cyanobacteria over the last 2 years.

5.3.1. CRAFTING MATERIALITY OF THE LIVING CYANOBACTERIA ARTEFACT

Viability of the Habitat

The primary objective of the artefact is to create an environment that fulfils the basic habitat requirements necessary to maintain cyanobacteria's metabolic activities and their functional potential in air purification. Cyanobacteria rely on light, water, carbon dioxide and other inorganic substances for their survival. This requires the habitat to allow for sufficient openness to facilitate permeation of light and gases (oxygen and carbon dioxide) while maintaining humidity levels. On the other hand, the habitat should also ensure safety for both humans and the cyanobacteria, by minimising risk of contamination, which could result from the growth of competing microorganisms that might threaten the viability of the cyanobacteria. Additionally, it should prevent any inadvertent leakage of cyanobacteria into the human environment. To address these contrasting requirements of openness (for light and gas exchange) and enclosure (for the safety of cyanobacteria and humans), we explored various potential materials (e.g., agar, calcium alginate hydrogel, PDMS silicone rubber and other types of silicone rubbers). After careful consideration, we selected PDMS silicone rubber—whose suitability for supporting microbial viability had been demonstrated in a previous scientific study [64]. PDMS silicone rubber is a highly robust, processable, gas-permeable, adhesive, transparent and biocompatible material. These qualities enable it to allow passage of light and gases while providing a clean and humid environment that supports the survival of cyanobacteria for over a month by maintaining its photosynthetic activity. We used PDMS rubber as a canvas material for encapsulating cyanobacteria within its cavity.

Surfacing Livingness and Temporality

A crucial step of caring for cyanobacteria involves understanding and tracking their living states over time. An effective indicator of their growth state is their photosynthetic activity [65]. To surface the cyanobacteria's photosynthetic activity, we explored various methods through ideation (figure 5.1). Ultimately, we opted for a well-established protocol using a pH-indicating solution composed of a proprietary mix of dyes (Bio-rad, USA). By implementing this solution, a living artefact can signal the absorption of carbon dioxide by cyanobacterial jelly beads during photosynthesis, manifesting as a colour change from yellow to purple in a matter of minutes. Building upon this technique, we further explored diverse jellification possibilities for both cyanobacteria culture and the pH indicator solution (figure 5.2). We focused on jellification of both substances simultaneously to form a jelly material, which could maintain its form and thus be easier to integrate into our artefact. Figure 5.3 shows how this jelly material surfaced photosynthetic activity of cyanobacteria through colour change. However, it is important to note that the jellification of both substances slows down the colour change. Consequently, the indication of photosynthesis takes several hours to manifest (figure 5.3). We think this compromise in terms of temporality is acceptable for our research. In designing the colour composition, we deliberately avoided incorporating any distinguishable patterns or shapes. This decision was made purposefully to maintain an ambiguous living aesthetic devoid of explicit connotations.

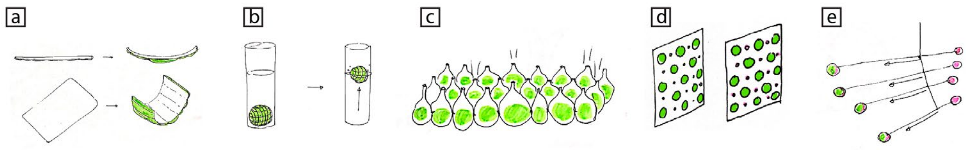


Figure 5.1.: Initial sketches depicting possible ways to surface livingness of cyanobacteria: a) bending, caused by the gas produced by cyanobacteria during photosynthesis; b) floating, driven by the gas produced during the photosynthesis; c) making sound, through a special mechanism according to the gas produced during the photosynthesis; d) colour changing, caused by substances produced during photosynthesis; e) un-balancing, due to depletion of nutrients as the cells reproduce.

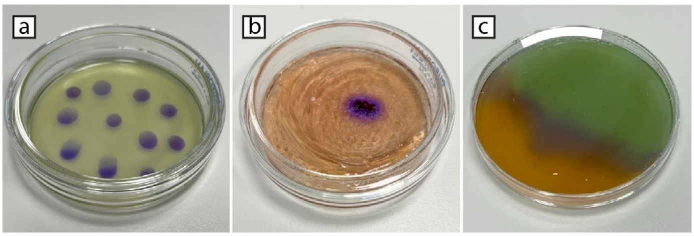


Figure 5.2.: Explorations of different compositions of cyanobacteria culture and the pH indicator in liquid and jelly forms for colour indication: (a) both cyanobacteria culture and the indicator are liquid; (b) both substances are jellified (first, the cyanobacteria culture is jellified into beads and embedded into the indicator, then the indicator is jellified); (c) both substances are jellified at the same time.

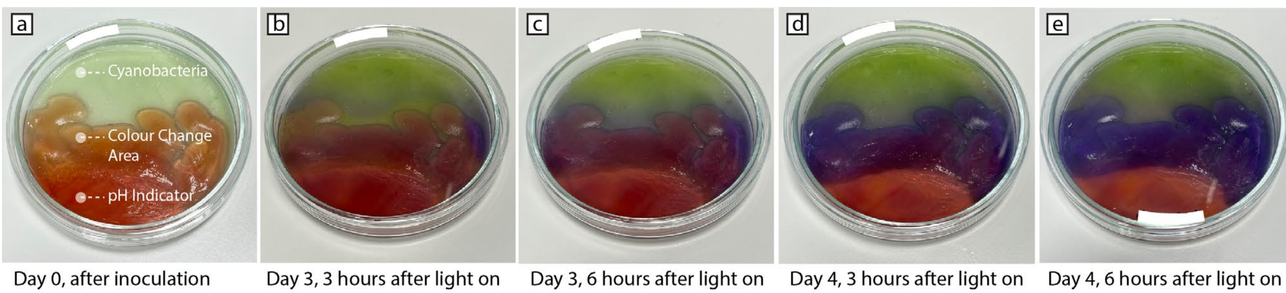


Figure 5.3.: The intensity of Cyanobacteria's photosynthetic activity surfaced by the colour-changing jelly material, from low (a), medium (c) to high (e). The cyanobacteria appeared greener over a few days, and the pH indicator showed a purple hue over a few hours after light was turned on in the incubator.

Performativity and Multi-situatedness of the Artefact

It is imperative that the artefact possesses the inherent ability to prompt a wide array of performances from people. In light of this consideration, we purposefully opted for a highly elemental and ambiguous form for the artefact, consciously refraining from incorporating explicit references to any particular utilitarian object, such as a vase. This decision ensures that the artefact remains receptive to multiplicity of interpretations [66] from people. To adapt effectively to the nuanced variations in domestic lighting conditions, the artefact needs to be multi-situated. In achieving this, we drew on the tuning/making of performativity [57][30], highlighting the material's performative qualities, which could be harnessed to make the artefact versatile in terms of its placement within a domestic space.

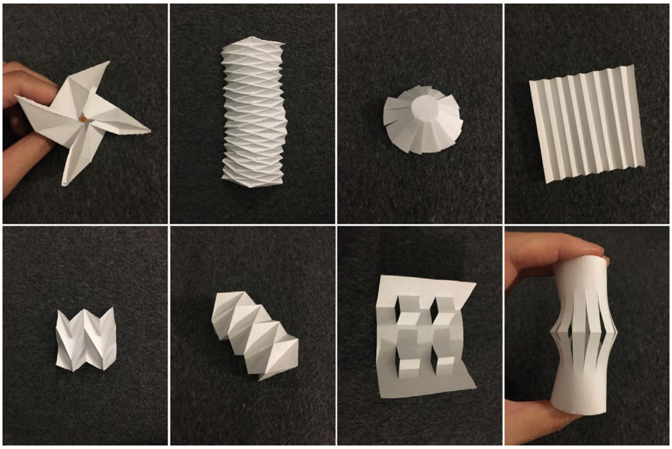


Figure 5.4.: Initial paper mock-ups to explore diversity and degree of performativities through which light received by the material surface can be adjusted

Amongst the habitat elements crucial for cyanobacteria, we focused on light as the element that participants could modify through their interactions with the artefact. Light was chosen because it is easily perceivable and adjustable within the shared domestic environment. Within our team, we engaged in an iterative design process involving paper mock-ups (figure 5.4), material tinkering (figure 5.5), and in-situ testing of a proof-of-concept (figure 5.6). These phases were carried out with the primary aim of gaining insight into how different alterations of light reception by a material can be accomplished through the material's performative qualities. To delve into the diversity and degree of performativity possibilities, we departed from utilizing paper mock-ups, deploying origami and kirigami techniques to create intricate light and shadow patterns. In this process, however, we opted for a seemingly simple sheet form devoid of explicit cues of specific affordances. This choice was deliberate, as this form inherently harboured the ambiguity and openness essential for enhanced performativity.

Given that the artefact essentially serves as a viable habitat for cyanobacteria, our material options were constrained to certain requirements (cf. section 5.3.1). We have considered conventional options to maintain microbes alive, such as agar plates or liquid culture in a glass flask. However, these material compositions are neither stable nor flexible enough to elicit from people the diverse creative performances we aim at (e.g., folding, sticking, and hanging of the artefact). Alternatively, we explored a method to encapsulate cyanobacteria that had been inoculated on a piece of paper, in a hydrogel (calcium alginate), as an initial way to form a simple-sheet material. Through tinkering with this technique, we discovered that thinner hydrogel yielded superior performativity, facilitating easy folding and rolling. The material's stickability enabled it to attach to objects (figure 5.5), while its transparency enabled light—a crucial element for the microbes—to pass through, allowing people to place the artefact at locations of light exposure. However, the material's fragility posed a challenge to our longitudinal study involving extensive participant interaction with the artefact.

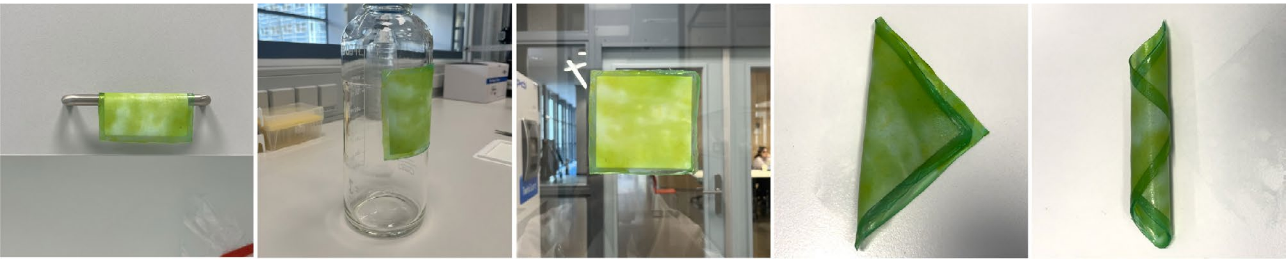


Figure 5.5.: Tinkering with a hydrogel material to explore potential performativities

As a robust alternative, we continued to explore PDMS silicone rubber, which, simultaneously, was identified as a suitable habitat material for cyanobacteria as mentioned in the previous subsection. We first confirmed its flexibility and adhesiveness by casting thin sheets without involving the microbe. Then, by encapsulating the microbial jelly, we made an initial prototype as a proof of concept: a 120 mm by 120 mm square sheet around 10 mm thick, enclosing a round cyanobacteria-pH indicator jelly. The sheet had to be thicker than the ideal thin sheet, due to the need to encapsulate the jelly. The artefact was applied in in-situ testing by the first author, where she lived with and cared for it for a week, to assess its performativity and viability in a domestic context (figure 5.6).

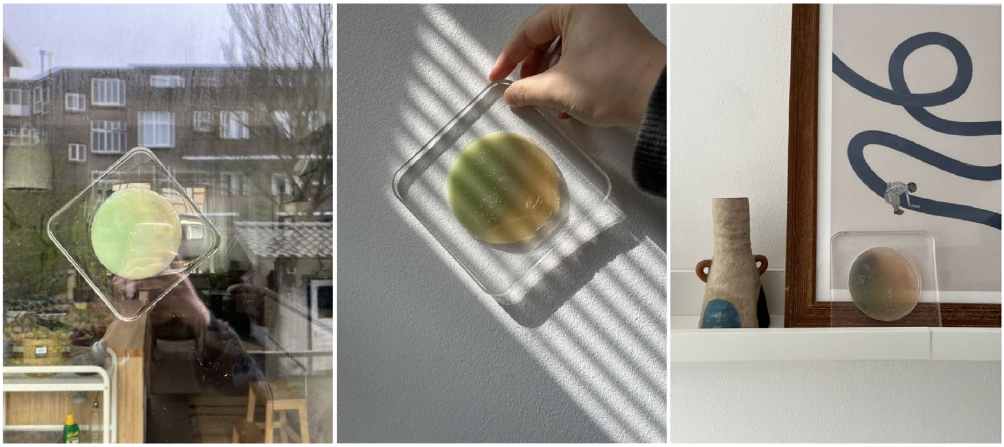


Figure 5.6.: A proof of concept for assessing performativity and viability in domestic context

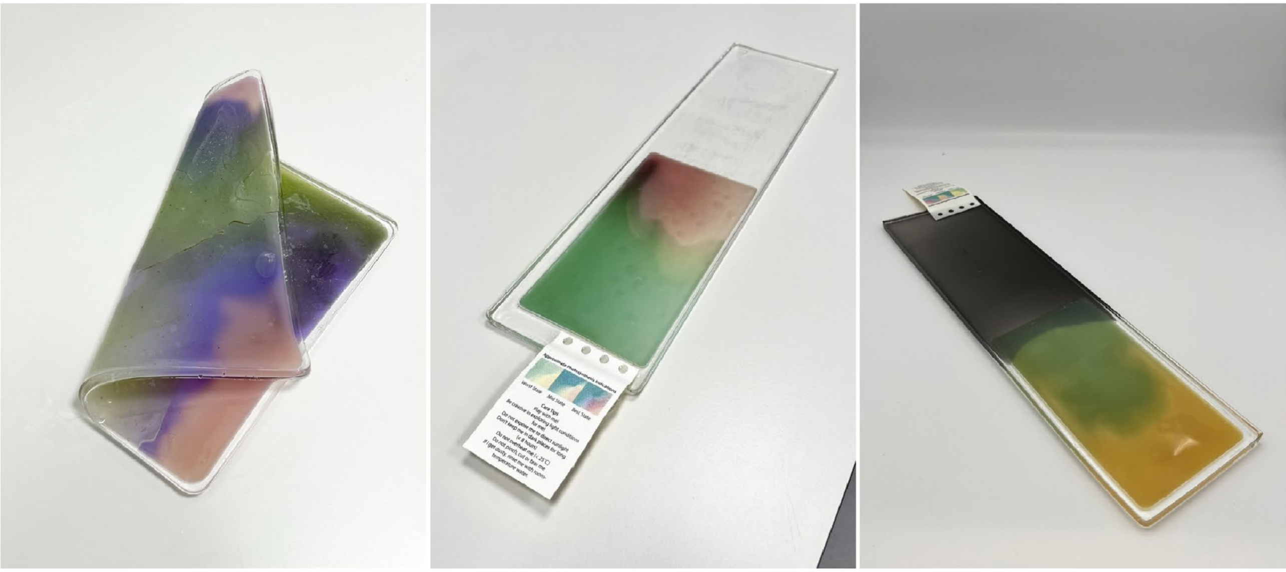
The adhesiveness and transparency worked effectively, enabling a novel interaction wherein the artefact could adhere to a window to receive more light. However, limitations arose due to its small size and thickness, hindering various light-altering forms (such as folding) and attachment methods (such as hanging), apart from propping against other objects. Additionally, the round disc shape of the cyanobacteria jelly was associated with a “finished product,” limiting creative interpretations. Furthermore, we recognized the need to offer a “shade option” within the artefact itself, as excessive light could prove detrimental to the organism. Our subsequent iterations (figure 5.7) prioritised reshaping the artefact to offer enhanced flexibility in attachment and capacity to provide shade to the cyanobacteria through folding. Consequently, our artefact now possesses properties of flexibility, adhesiveness, and the ability to be suspended. It features a darkened half that can offer shade when folded, thus addressing the light intensity concern.

Care Label

We created a care label (figure 5.8) attached to the artefact, providing participants with easy access to information during their interactions. The label informed participants of approximate colour indications of the artefact’s well-being state, and offered suggestions that encourage participants to engage in playful and creative exploration of light conditions for the artefact, while cautioning them against potential harm. The care tips are as follows:

> *Play with me!*
> *Be creative in exploring light conditions for me! Do not expose me to direct sunlight.*
> *Don't keep me in dark places for long (< 8 hours).*
> *Do not overheat me (< 25°C). Do not pinch, cut or tear me.*
> *If I get dirty, rinse me with room-temperature water.*

Figure 5.7.: Final iterations on shape, size and colour of the artefact
Figure 5.8.: Care label attached to the Living Cyanobacteria Artefact



Making the Living Cyanobacteria Artefact

The Living Cyanobacteria Artefact is a soft, flat and rectangular object with a silicone outer shell. It encloses a thin layer of jelly that contains living cyanobacteria and the pH indicator, which surfaces the photosynthesis of the microbes through colour change. Below we outline the making steps of the artefact.

Step 1 Jellification of cyanobacteria liquid culture and the pH indicator solution First, agar solution infused with growing medium (BG11) and calcium chloride solution (2.5% w/v) was formulated and autoclaved for sterilization. Within a biosafety cabinet, the heated agar solution was poured into a pre-made plastic mould (190 mm by 100 mm) and let to solidify. Second, a sodium alginate solution (5% w/v) was mixed respectively with a medium-green cyanobacteria (*synechocystis* sp. PCC6803) liquid culture and the pH indicator solution, both at 1:1 volume ratio. Third, both liquid mixtures were poured simultaneously onto the solidified agar within the mould, from opposite ends. They intermixed and diffused into each other in the middle of the mould, forming a thin layer of approximately 2 mm thick. This layer was then left to jellify for about 1 hour. Once jellified, the upper layer was carefully peeled off from the mould and placed within a sterile petri dish.

Step 2 Casting the bottom silicone rubber layer In a fume hood, two components of PDMS silicone rubber were mixed in a 10:1 ratio and evenly divided into two plastic containers. A black silicone pigment was added to one of the containers and thoroughly mixed. Subsequently, both silicone mixtures were poured into a pre-made mould (400 mm by 110 mm) from opposite ends, converging at the midpoint. This formed an approximately 3 mm-thick silicone layer. The silicone was then cured for 4 hours at 60 degrees Celsius in an oven.

Step 3 Preparing the care label Care instructions were printed onto a cotton canvas material using a laser printer. Following this, the label was punctured with several holes at one end, immersed in silicone rubber, and cured at room temperature for over 48 hours.

Step 4 Casting the top silicone rubber layer The previously created bottom layer of silicone rubber was kept in its plastic mould. The cyanobacteria-pH-indicator jelly was laid on top of the transparent section of this bottom layer. Simultaneously, the care label was affixed on the other end onto the silicone rubber. Same as in step 2, two components of PDMS silicone rubber were mixed in a 10:1 ratio, and poured into the mould. This process formed a top layer that covers the jelly sheet and the punctured area of the care label. The artefact was then cured at room temperature for 48 hours. The cured artefact (figure 5.12) measured approximately 400 x 110 x 8 mm.

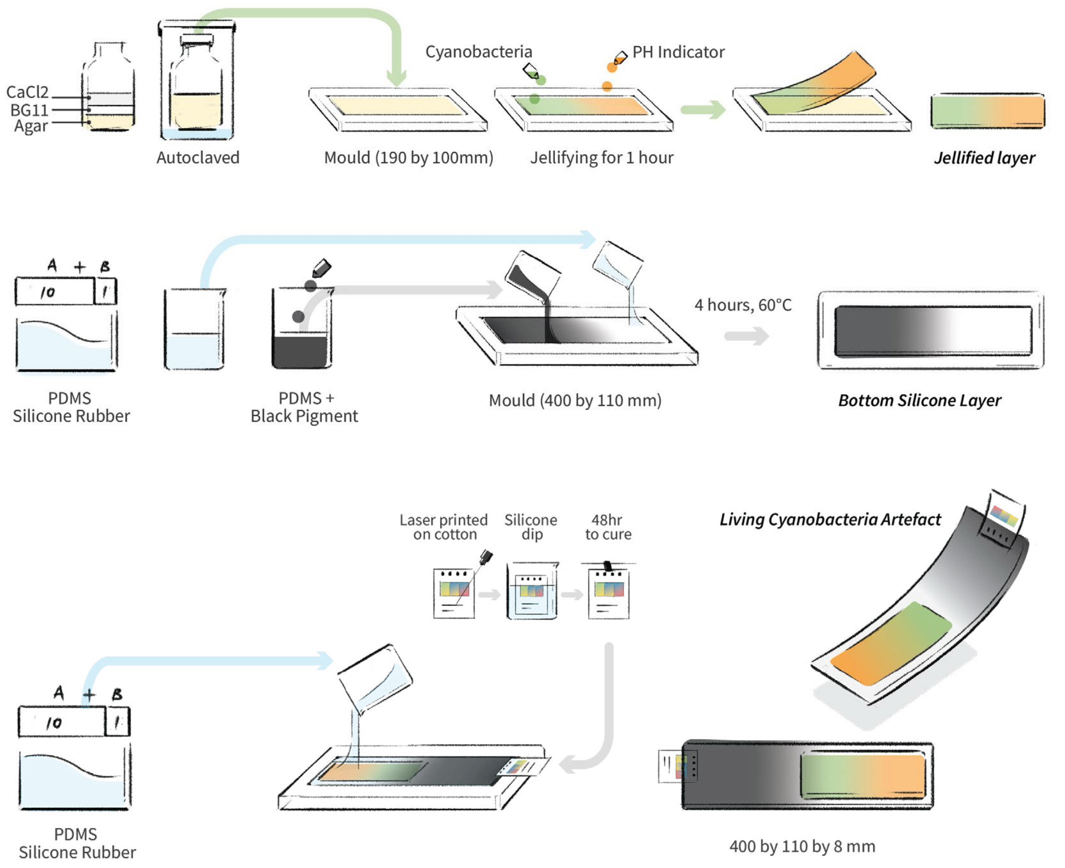
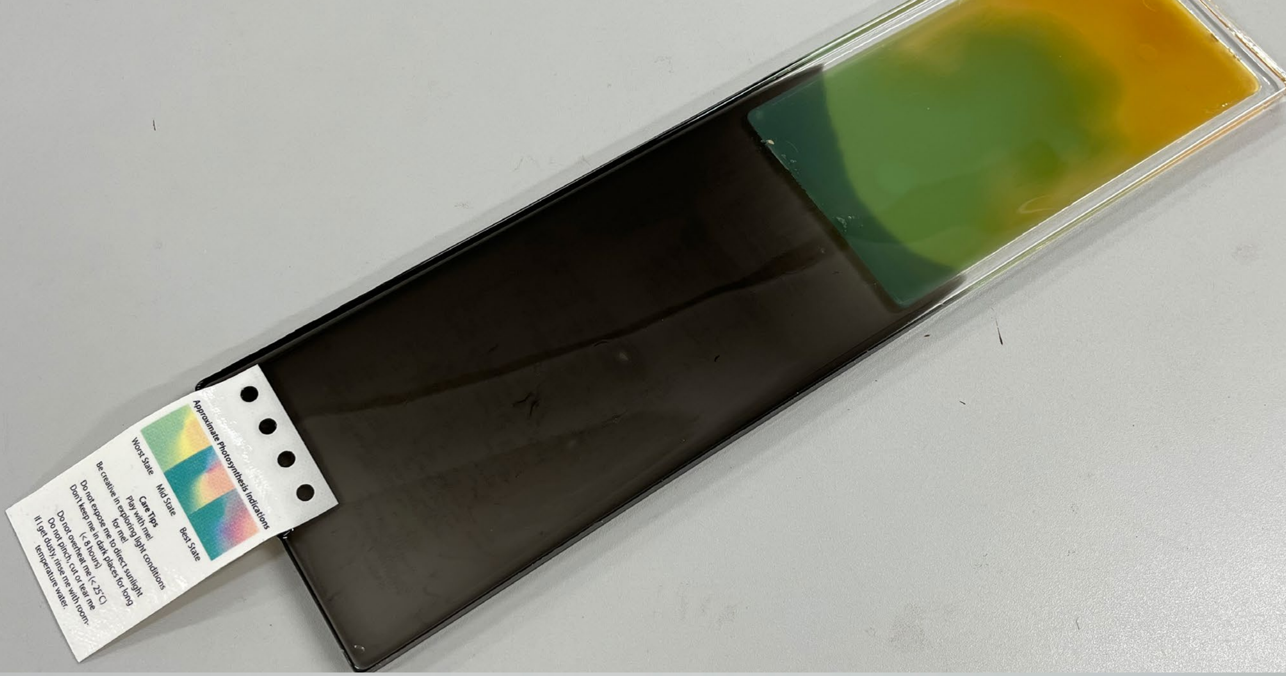


Figure 5.9.: Step 1, Figure 5.10.: Step 2, Figure 5.11.: Step 3 and 4 of making the Living Cyanobacteria Artefact

Figure 5.12.: The Living Cyanobacteria Artefact



5.3.2. THE STUDY

Our study was centred around addressing several key questions. First and foremost, we sought to understand the diverse ways in which people express care for the potential air-purifying Living Cyanobacteria Artefact, and the underlying motivations behind their chosen approaches. Furthermore, we were keen to explore the significant role that materiality plays within this context, shedding light on how it shapes caregiving practices.

Participants	Age	Gender	Roles associated with care for other- than-human living beings
P1	68	female	Plant lover / lifetime gardener
P2	51	transgender	Cyanobacteria photographer / cat keeper
P3	32	male	Self-identified plant “killer”
P4	60	male	Microbiologist
P5	34	female	Beer brewer / cat keeper
P6	27	male	Plant lover
P7	35	female	Kombucha brewer / plant lover
P8	28	female	Self-identified plant “killer”

Table 5.1.: Overview of participants

Participants

Our study was conducted with eight participants (table 5.1), between the ages of 27 to 68, and from fairly distributed genders. Our selection criteria for participants included 1) that they lived within the Netherlands, and 2) that they had previous and varied experiences of caring for other-than-human living beings. Some of them did not take care of plants well (i.e. claiming themselves to be a plant “killer”), while others took care of living things as a hobby, obligation, or job. The people who took care of living things as a hobby enjoyed taking care of plants or gardening, while those who took care of them as an obligation had to do so for making beer or kombucha. Lastly, some people had jobs where they took care of living things, such as biologists who worked in laboratories. The diverse experiences in caretaking may increase risk of “care failure”, e.g., with participants who claimed to fail in plant care. However, it ensured that we could observe a wider range of motivations and creativity in caretaking for a novel living being. We did not recruit people who had children under 12 years old, to minimize any possible damage or accidental ingestion of the artefact. All participants undertook the study voluntarily.

Figure 5.13.: Delivery of the Living Cyanobacteria Artefact and its care instructions to a participant

Procedure

We first sent out invitation letters to potential participants, in which we explained that we were interested in what it is like for people to live with living artefacts—everyday artefacts containing living organisms for advanced functionalities (e.g., to purify air, to self-repair, etc.). We asked them to live with and care for the Living Cyanobacteria Artefact over two weeks at their homes, and to share their daily experience and reflections with us.

The study was undertaken in three phases. First, we delivered the artefact to participants' homes, accompanied by instruction cards that introduced the artefact and the study requirements (figure 5.13). These cards informed participants that the artefact contained living cyanobacteria, which are capable of absorbing CO_2 from their surroundings and emitting fresh oxygen, thus potentially purifying the air. Participants were directed to position the artefact in locations where air purification was considered necessary and light conditions advantageous for its well-being. Additionally, we presented the artefact's preferred light conditions, and its colour changes signalling its well-being state. They were asked to take a photo of the artefact and its surroundings whenever they observed a colour change, and in case they relocated it or altered its form. They were prompted every 2 or 3 days by the first author to share texts or photos through their preferred digital platforms (e.g., WhatsApp and email). Furthermore, they were also encouraged to assign nicknames to the artefact, as a way to familiarize with it. Complete instructions can be found in the Appendix. Upon delivery of the artefact, we conducted an initial interview to gain insights into the participant's routines and took a photo of their living rooms. The second phase of the study involved semi-structured interviews, lasting 30 to 60 minutes, conducted at the one-week mark of the study. At the end of the study, we conducted a follow-up interview. Most interviews took place at participants' homes, with four of them taking place over Zoom. The questions were designed to build upon the cumulative nature of the study, with second-week interview questions shaped by the responses gathered during the one-week interviews. In total, the study generated approximately 6 hours of verbal interview data, along with 79 self-reported and 64 researcher-captured photos collected after each site visit.

Interview Questions

Our interview inquiries focused on the evolution of care practices. It's worth mentioning that we deliberately refrained from directly probing participants about the concept of "materiality." Instead, we gleaned insights about its influence by synthesizing evidence from their comprehensive encounters with the artefact, thereby mitigating potential biases and ensuring that our questions remained accessible. In formulating our interview questions, we drew inspiration from Maria Puig de la Bellacasa's feminist care ethics framework, which has been increasingly discussed in recent HCI and design venues (see, for example, [3, 26]). Puig de la Bellacasa emphasises the interplay between "knowing" and "caring," and unpacks care towards the more-than-human worlds with three mutually dependent and challenging aspects: *labour/work, affect/affections, ethics/politics*. She also highlights the need to "make time" for care doings for other-than-human living beings. We also incorporated the notion of *mutualistic care* in biodesign [28] in the formulation of our questions. Specifically, we focused on how care relations with living artefacts can be reciprocal and evolving, and what role living aesthetics (i.e., how changes in living materials are experienced by people) plays in the establishment of mutualistic care, within this framework [28].

Accordingly, we synergized interview questions into the following five categories (table 5.2): 1) Knowing and relating to the organism: How are care actions

Unpacking care	Interview Questions (after a week living with the living artefact)	Interview Questions (after two weeks living with the living artefact)
Opening	What is it like to live with [nickname] so far? Do you want to share anything specific you experienced last week?	How was your second week with [nickname]? Is there anything that has changed?
Performances and reciprocity	How did you take care of [nickname]? Can you show me where and how you placed [nickname] at home? And, why?	What else did you try? And, why?
Knowing and relating to the artefact	How did [nickname] respond to your actions? And, why do you think it responded in that manner?	Did you notice anything different from the previous week? Why do you think that happened? And, how did you feel about it?
Affection towards the artefact	How did you feel when you noticed changes in [nickname]? Why did you feel that way? What other feelings did you have towards [nickname]? Why?	How did your feelings change? Did you feel some- thing else?
Making time for care	How much time did you find yourself setting aside to look after your artefact ([nickname])? Did it change your daily routine in any way? And if so, how?	Did anything change in the second week?
Motivations of care	Do you feel motivated to look after [nickname]? And why? What would motivate you even more in looking after [nickname]? Does your experience with [nickname] remind you of any other experiences you had of caring for other things, for example, a person, an animal, a plant, or other living things? And, how?	Did you feel more or less motivated this week? And why? What would motivate you even more in looking after [nickname]? How much of a good carer do you think you were over the two weeks? What do you think would help you to improve your care to [nickname]?

Table 5.2.: Interview questions of the one-week and two-week interviews

facilitated through noticing the living aesthetics of the artefact? 2) Affection: How does affection evolve through care actions towards the artefact? 3) Performances and reciprocity: How do care actions evolve? How do participants navigate their performances between the function of the artefact—air-purifying—and their care for the artefact? 4) Making time for care: How does taking care of the artefact influence people's everyday routines? 5) Motivations of care: Why do people care for the living artefact?

Data Analysis

Following the interviews, audio recordings were transcribed. Coding and thematic analysis [67] were carried out by the first author on the photographs reported by participants, the text messages from participants during the study, and the transcribed interview data. Selective coding was used, to analyse the data under two interrelated lenses to address our research question: 1) the whys and hows of care for the artefact, and 2) how the artefact's material qualities influence care towards it. The initial coding was discussed among the first, second and last authors, which resulted in the repositioning and renaming of certain themes. Adapted themes, which will be presented below, were finalized through a discussion session by all authors.

5.4. RESULTS

We organize our results into two subsections: *the whys and hows of care for the artefact*, and *material qualities and care practices*. Accordingly, we present a narrative that initially delves into the motivations and performances of care. Subsequently, we present observations on intricate connections between materiality and the nurturing of care practices.

5.4.1. THE WHYS AND HOWS OF CARE FOR THE ARTEFACT

We categorize the "why and how" into four themes, shedding light on the nuances behind participants' caretaking experiences. It's important to note that multiple motivations often coexist and can influence caregiving practices in various situations. However, for the sake of practicality and to facilitate the analysis of our extensive dataset, we initially organized these motivations into separate categories.

Care Practices Motivated by Livingness

A prevailing motivation observed among participants was a deep-rooted instinct to care for living entities. Many participants expressed enjoyment in living with and taking care of other-than-human life forms, such as plants, animals (e.g., young livestock), or even microorganisms (e.g., those used to cultivate kombucha). Consequently, their care practices were significantly influenced by their established ways of caring for familiar living things. For instance, some participants placed the artefact close to their house plants that share comparable light requirements (figure 5.14). This arrangement facilitated the incorporation of attentive interactions with the artefact into their existing routines of tending to their plants, thus serving as a gentle reminder to allocate dedicated intervals for its upkeep. Participants derived a similar sense of satisfaction from taking care of the Living Cyanobacteria Artefact as they did for plants. For example, they expressed delight in witnessing the microbes in the artefact “growing," and seeing it "responding" to their care actions. These observable transformations in the living artefact motivated them to provide good living conditions for its well-being.

Figure 5.14.: Participants placed the artefact in close proximity to their house plants that share comparable light requirements

Care Practices Motivated by Curiosity towards New Life-form

Introducing a new life form, cyanobacteria, into everyday life made our artefact a novel experience for all participants. One participant expressed excitement over the realization of embedded microbes, highlighting a new and futuristic "ecological connection" which presented them a unique opportunity to "communicate" with these microbes. Several participants mentioned experiencing a "new enjoyable responsibility" elicited by the artefact. One participant was particularly inquisitive about the working principle of the artefact, while another participant conducted experiments to understand how local light conditions influenced its colour change, by placing multi-coloured LEDs (figure 5.15, a) or a shade-introducing coin on its surface.

Figure 5.15.: Various care performances elicited by the new life-form: a) conducting experiments to understand how local light conditions influenced its colour change by placing a red LED light; b) letting the artefact stay in an initially identified suitable location to "settle down" to avoid risk; c) identifying a location with better light conditions for the organism through trial and error.

Participants encountered difficulty in aligning their care actions with the well-being states of the artefact in the beginning. As such, some participants retained a risk-aversion attitude throughout the study, avoiding excessive experimentation. Once they found a suitable location for the artefact, they felt content with the artefact "doing ok" there (figure 5.15, b). Conversely, some took a more exploratory stance, adjusting their presumptions through trial and error. For instance, one participant, who had prior experience working with cyanobacteria, initially felt confident in her judgement regarding light conditions for the artefact's initial placement. However, the artefact did not exhibit an anticipated purple colour. After one week, the participant decided to expose the artefact to more light, resulting in its better state, marked by a purple hue (figure 5.15, c). Over time, all participants became more attentive and patient towards the artefact. As a result, they could anticipate the colour change when they repositioned the artefact.

Participants shared a common transition from excitement to relaxation while living with the artefact. It became evident that they allowed the artefact to ultimately "do its own thing." In some cases, novel care routines emerged towards the end of the second week. For instance, one participant developed a new practice of checking the status of the artefact both in the morning and evening. Another participant regularly engaged in "documentation" to closely observe subtle colour changes, which served as a reminder of being attentive and caring.

The new life form sparked participants' imaginations, leading them to envision novel artefacts and care practices that extended beyond the current design. For instance, some suggested the idea of providing bodily warmth to the microbe through a wearable artefact. Others imagined looking for new households with more favourable light conditions for the artefact, which highlighted the possibility of nurturing care with novel social engagements.

Care Practices Motivated by Mutualism

Participants felt also motivated to take care of the artefact because of its potential functional benefits. For instance, some expressed an apparent disappointment of not knowing the tangible results of air purification, stating "I don't know if I will keep enjoying living with it because I don't notice so much difference in the oxygen." One of the participants named the artefact "Oxy," indicating the significance they placed on its functional value. Many participants had doubts about its functionality, with one remarking, "At this scale, I don't believe enough is happening." Several participants expressed a wish for a numerical indication of how much air the artefact had purified, which might increase their interactions with it. Furthermore, one participant took the artefact to their workplace, a beer brewery (figure 5.16). They intended that it could help absorb carbon dioxide generated by the brewing process (for the well-being of humans) while receiving bright light from the brewery's interior (for the microbe's well-being). This evidence emphasized mutualism as a drive for care practices.

Figure 5.16.: A participant brought the artefact to a beer brewery where they worked, with the intent for the artefact to assist in absorption of carbon dioxide generated by the brewing process (benefiting humans), while receiving bright light from the brewery's interior (benefiting cyanobacteria).

Care Practices Motivated by Joyful Interactions

Joyful interactions with the artefact, also referred to as ludic and playful interactions in HCI ([68–72]), triggered participants to persist in their care towards the artefact. These interactions were mainly driven by a sense of accomplishment given by achieving what participants considered a "better colour." Upon achieving visually delightful appearances, some participants took a moment of pause to enjoy the artefact's beautiful hues, describing it as a "slightly meditative act." One participant expressed a particular fondness for the colour purple (figure 5.17, b) and was motivated to diligently care for the artefact to achieve a fully purple appearance. Two other participants mentioned that the artefact was like a splendid piece of art radiating "good energy" and "vibe," with one of them naming the artefact "Hoopla!"—a joyful expression according to the participant. To enhance these joyful interactions with the artefact, participants employed various care strategies. Placing it in close proximity for constant observation was a common approach, which allowed regular admiration of the "beautiful" artefact in the background of everyday tasks, such as dishwashing. One participant chose to hang it on the edge of their dining table, ensuring instant visibility from any angle upon entering the room (figure 5.17, a).

Figure 5.17.: a) The artefact placed in close proximity for constant attention from the participant; b) A participant showing the "beautiful" purple hue in the artefact during our interview.

5.4.2. MATERIAL QUALITIES AND CARE PRACTICES

The material composition supported cyanobacteria's viability effectively. In seven households with sufficient light intensity, caring for the artefact was generally perceived as "enjoyable," or even "too easy" by participants. This was because no other care actions besides finding a suitable location were needed, although participants struggled in the beginning. In one particular household with relatively limited natural light, despite the participant's efforts, such as placing the artefact in the brightest spot in the house, the artefact faded its colour after one week (figure 5.18, b). In their final reflections, this participant suggested passing it on to a more suitable household, as an alternative way of "care."

Several participants expressed how the beauty of the artefact made them “immediately attached” to it, taking their care responsibilities more seriously than they would with a simple bottle of culture. They appreciated the vibrant colour change resulting from the cyanobacteria’s photosynthesis since it allowed them to better grasp the state of well-being of the microbe. They commented on how this is quite different from situations like “beer brewing microbes that are hidden inside wooden buckets,” where their functions and well-being remain concealed. The intensifying green hue of the microbe prompted perception of "growth." However, participants expressed a dilemma; whilst valuing the ambiguous colour change as the artefact’s distinctive "language," they also desired more precise colour references on the care label and detailed light intensity information. Others expressed a desire for more “immediate change” to enhance their understanding of cyanobacteria’s well-being. The form and texture of the artefact also shaped the perception of livingness and thus caregiving practices. For instance, one participant compared the artefact with plants, noting that the three-dimensionality and variety of forms of plants offer great aesthetic value to the living space. This motivated them to care for plants more actively than the relatively two-dimensional artefact.

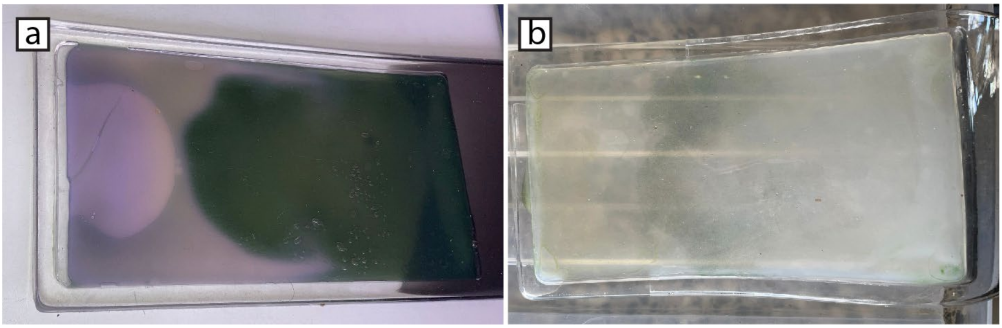


Figure 5.18.: a) An artefact which survived two weeks b) An artefact which faded its colour after one week

Participants explored various ways to place the artefact in the home. Towards the end of the study, many participants had evolved their own unique care practices. The silicone rubber’s intrinsic stickability prompted one participant to stick the artefact onto a window (figure 5.19, a), ensuring maximum light exposure in a north-facing living space. Another participant utilized the artefact’s bendability and transparency to create a light-receiving arch on their reading desk for “catching the light.” (figure 5.19, c) Some participants hung the artefact on a curtain rail near a window (figure 5.19, g), or a door frame in the garden (figure 5.19, e). The artefact's darkened section was folded by some participants to provide shade to the cyanobacteria when ambient light was thought to be too intense (figure 5.19, b). Some participants viewed the artefact more as a static art piece rather than an interactive object to carry around or engage with, compared to a cube- or ball-shaped artefact, such as a "marimo moss ball." Others refrained from "playing" with it freely, as they perceived the microbial layer as too thin and fragile. Some participants were hesitant to touch the artefact frequently because the adhesive silicone rubber easily became "dirty."

5.5. DISCUSSION

The deployment of the Living Cyanobacteria Artefact in everyday life has provided insights into how its material qualities influenced participants' caregiving practices. In this section, we organize these insights into three distinctive roles that materiality can play in nurturing care practices towards living artefacts and highlight dimensions to capitalise on these roles in the design of living artefacts. We also broaden the discussion to encompass the broader opportunities and challenges associated with designing and caring for living artefacts. And to close, we acknowledge the limitations of our work and suggest avenues for future research in this area.

5.5.1. ROLE OF MATERIALITY IN THE CREATIVE UNFOLDING OF CARE PRACTICES

Increasing Habitat Resilience to Support Care Labour

This particular aspect focuses on the artefact's viability. This is largely influenced by the material properties resulting from the combination of the hydrogel and PDMS rubber. This composition ensured a high chance of survival amongst distributed households. Another way to increase resilience could be to design the habitat in a semi-open manner [73] in such a way that additional nutrients can be provided to the microbe or living cells can be propagated to create a new artefact. Such habitats could potentially enable richer social interactions, such as those stemming from the act of sharing "offspring" artefacts with other people. They would also allow direct engagement with cyanobacteria, hence fostering a sense of connectedness with other life forms. For further explorations in terms of openness, designers may also look into diverse material compositions, for instance, by integrating shape morphing materials in artefacts for opening

Figure 5.19.: Diverse explorations from the participants in an attempt to find the most suitable place for the living artefact. a) Sticking the artefact on a window b) Folding the dark section c) Bending the artefact and fixing it to other objects d) Folding and hiding the artefact behind another bottled cyanobacteria culture e) Suspending the artefact on a chair arm f) Suspending the artefact on the back of a sofa g) hanging the artefact on a curtain rail

and closing nutrient and organism flows, e.g., bio-based and hydrogel-based morphing textiles [74, 75].

Surfacing Livingness to Enhance Care Knowledge

This aspect concerns the role of materiality in surfacing livingness of microbes. This contributes to deepening a novice's knowledge of microbes' well-being and shaping affection and appreciation in caring for them. Without surfacing, the slow accumulation of cyanobacteria's green colour, spanning days and weeks, would be difficult to notice to unaided human eyes. Our use of pH-indicating material manifested cyanobacteria's photosynthesis through faster and more vibrant colour changes, effectively addressing human-microbe "temporal dissonance" [21](p.821). Given our artefact's predetermined temporality resulting from the pH indicator, we anticipate future designs to incorporate materials and technologies to surface microbial metabolism with divergent temporalities [32, 76, 77]. For instance, designers could consider adding a translation strategy [23](p.10) in displaying cyanobacteria's well-being with a fast-responding material [21], that could elicit urgent care responses from people whilst allowing the overall long-term accumulation of microbial livingness to be appreciated (ibid. p.824).

Another important consideration concerns managing the semantic fitness of living artefact displays [23] to effectively communicate livingness, which inherently motivates care practices. The manifestation of livingness through the artefact often requires material qualities shared with familiar living beings, such as plants. For example, the natural green hue of cyanobacteria was interpreted by the participants as "a sense of growth" or the bacteria being "happy." In contrast, the rectangular shape and two-dimensional form of the artefact diminished its perceived livingness, because people at first had the impression that the artefact was inorganic. In light of this, we encourage future research to explore three-dimensional forms and textures to embody temporal forms of familiar living things (e.g., by canvassing [23] (p.7) cyanobacteria in leaf/plant-like configurations). Investigating this approach could potentially enhance the experience of the artefact as "being alive," and thus increase motivation for caregiving.

Tuning Performativity to Elicit Exploratory Care

The performative qualities of the artefact (e.g., its stickability) played a crucial role in encouraging participants to actively explore various ways of placing the artefact in the home for both functionality and its well-being. This was key in leading to habitual care practices. Though our artefact's simple form facilitated creative ways of care, the results revealed an opportunity to tune the form of the artefact towards certain experiences, e.g., "intimate engagement" and "playfulness." For example, in the iteration of our artefact, we could consider designs that are "toy-like," to solicit playfulness of interaction. We call for attention to a dimension between exploratory and prescriptive approaches in crafting performativity. High ambiguity in form introduces uncertainty in how to care, risking critical functions and the well-being of vulnerable species. Striking the right balance between open-endedness and specified guidance through form could facilitate people to be creative towards microbes' care practices and to understand their diverse needs, scales, agencies, and temporalities [73], while learning about the dynamic and unpredictable nature of living systems.

5.5.2. ON THE NATURE OF CARE: OPPORTUNITIES AND CHALLENGES

In this section, we delve into the broader implications of our study for the HCI community, with the goal of illuminating new design opportunities and avenues for the creation and care of living artefacts.

Tuning into the Evolving Nature of Care

Our findings illuminate the dynamic nature of care practices, which undergo transitions as individuals adapt their actions for the living artefact, progressing from improvisational to more established routines. Throughout this evolution, the performative qualities of the artefact play a pivotal role in identifying an optimal range of lighting conditions. However, it is through repeated acts of care that these practices can solidify into established care relationships. These ultimate practices tend to seamlessly integrate into people's existing daily routines. For example, one participant discovered that the artefact thrived in a specific corridor of the house. This inspired them to hang the artefact on the wall of the corridor, where it served as an art piece that the participant could check upon every day while walking by. To address this evolving nature of care practices, designers may need to incorporate ways for the artefact to be responsive and for relationships to change [78], for instance, by leveraging translation techniques [23] to make living artefacts more communicative of their diverse needs (e.g., [12, 26]). They must also be sensitive to and practise the design trade-off between dimensions of openness/variety vs. familiarity, allowing the living artefact to be adaptable to rapidly changing environments during the exploratory phase, and to be integrated at a unique position within specific human practices.

Nurturing Mutualistic Care

In our study, participants grappled with a contradiction when determining how to interact with the artefact, balancing functional benefits (i.e., self-care) against the care of the microbe. For instance, one participant regarded the artefact as a domestic air purifier, leading to an expectation that it should remain at home, even if the home environment wasn't ideal for its well-being. In contrast, another participant, who brought the artefact to her workplace for air purification, discovered that it struggled to thrive there due to inadequate lighting conditions. Eventually, she had to bring the artefact home, even though it meant compromising her own "self-care." Overall, establishing a sense of mutualistic care [28] proved challenging in our study. This challenge could be attributed in part to our framing of the artefact as a potential air purifier, thus limiting open-ended interpretations of its functionality. Consequently, we call upon designers to be meticulous in conceptualising the function of living artefacts, allowing mutualistic care relationships to naturally evolve within everyday practices of people who live with them. Designers might consider situating the artefact's openness within dimensions of variety and enable people to customise its functions to suit familiar daily practices, similar to the approach demonstrated by [79, 80] in the everyday design of connected things as “resources”. We posit that such an approach in the design of living artefacts has the potential to foster reciprocal relationships between the artefact and people who live with and care for it.

Designing for Multiple Dimensions of Care

Our study demonstrates that "good care" is nuanced and multifaceted, subject to a wide array of interpretations among individuals. For some, the mere acknowledgement that the microbe is alive constitutes sufficient evidence of good care. Others place greater emphasis on the effort exerted in the act of caring, prioritising the intention and diligence rather than the outcomes. Some critically evaluate their care-taking attitude, scrutinising the consistency and mindfulness with which they tend to the artefact. This rich tapestry of interpretations underscores a crucial point: there exists no universal understanding of what constitutes better care. Instead, it is a nuanced and context-dependent concept, moulded by the unique values and experiences of each individual. As we reflect on this diversity, we extend an invitation to future research in the field of HCI to embark on a journey of exploration. This exploration should involve mapping out the intricate dimensions of care [2]. By doing so, we can engage more comprehensively with the complex landscape of care, in accommodating diverse perspectives and expectations of people who may care for a living artefact. This holistic approach to design will ensure that the artefacts we create resonate with the various ways individuals conceive and practice care in their everyday lives.

5.5.3. LIMITATIONS AND FUTURE WORK

Our decision to conduct a two-week in-situ study was influenced by several factors, primarily centred around the current limitations of our artefact's lifespan of approximately a month. These limitations stem from two key observations made during our assessment of the proof of concept. Firstly, we noted a gradual decline in the artefact's colour contrast over time. This phenomenon could be attributed to the continuous diffusion of the pH indicator into the living part of the artefact. As this diffusion occurs, the artefact becomes less sensitive in indicating the well-being states of the embedded microbes. Secondly, we observed an unexpected issue related to the artefact's humidity levels. The microbial-embedded jelly within the artefact dried out within 45 days. This unexpected outcome resulted in the jelly's volume shrinking and the formation of air bubbles within the artefact's cavity. The exact causes of these phenomena remain subjects for further investigation. In our next iteration, we aspire to address these challenges by enhancing the longevity of the artefact, which will provide an opportunity to delve deeper into the evolution of care practices over a longer period.

We intentionally selected light as the initial habitat element to explore when investigating care practices for our microbial artefact. We recognize that the well-being of a microbial artefact is influenced by a range of complex environmental factors, including but not limited to temperature, humidity, and nutrition. However, to keep our initial technical and design explorations manageable and to ensure that the study remained accessible and comprehensible to participants, we opted to focus on one specific habitat element as a starting point. As anticipated, participants found the focus on light to be relatively "easy," although they encountered challenges along the way, and expressed their interest in practice care with multiple habitat elements. Building on this, we envision expanding our exploration to encompass multiple habitat elements. This broader perspective has the potential to depict care more holistically, capturing the intricate interplay of environmental factors that influence the well-being of the microbe within the artefact. We anticipate the need for in-situ investigations to gain a deeper understanding of how these complex habitat elements can collectively impact the microbe's well-being. Furthermore, our study approached cyanobacteria well-being through photosynthesis —a metabolic process integral to their growth and reproduction. Hence, the recognition of the microbe's well-being relied on how humans experience the changes in the artefact's temporal expressions which occur due to this metabolic activity. However, we envision significant potential in future research to explore methodologies, such as thing ethnography [81] to take perspectives and agency of other-than-humans (in our case microbes) into account in exploring such everyday exchanges and relations.

Our study aimed at probing a new design space and generating novel research questions at the cross-section of materiality and care in biodesign. This led to several decisions, including describing the artefact as a potential air purifier based on cyanobacteria's reported ability to capture carbon and release oxygen (cf. section 5.2.1). However, we prioritized participants' potential perception of functionality over the actual benefits of air purification. Participants were informed that the artefact could potentially serve as an air purifier, allowing us to investigate how they could navigate tensions between perceived functionality and care. This decision raised new questions, such as the significance of knowing the function of living artefacts in fostering care. Further exploration is needed to compare caregiving practices in scenarios where living artefacts offer more compelling functional advantages versus situations without them. Achieving this involves further enhancing the artefact's perceived functionality, considering technical aspects of cyanobacteria as an air purifier, such as an enlarged surface area of living biomass. Likewise, contrary to investigating diverse impact factors of materiality on nurturing care practices, we focused on developing an initial viable living artefact, acknowledging the limitations of our fixed design. We anticipate that future studies will delve more deeply into nuances of how different materials and their respective qualities (e.g., texture) distinctly influence care practices.

Expanding our perspective beyond the scope of our current study, we recognize the imperative to confront the complexities inherent in caring for living artefacts within real-life contexts. Such care practices are not always characterized by positivity and fulfilment; they entail a spectrum of experiences, much like any other form of care [3][50][46]. We deeply appreciate the tensions and dilemmas that have emerged from our study and intend to delve further into these intricacies. Our aim is to explore how these multifaceted human engagements with living artefacts, driven by care, can be made more seamless, multidimensional, decentralised, and ultimately mutualistic. To achieve this vision, we believe that our understanding of care through materiality can contribute to enriching the research landscape within HCI. We encourage designers of living artefacts to harness diverse mediums and approaches to engage individuals in creative thinking and action, fostering a culture of mutualistic care that transcends rigid design prescriptions. In doing so, we envision a world where care for our other-than-human living companions is an integral part of our shared existence.

5.6. CONCLUSION

Our research aimed at exploring the role of materiality in the everyday care of microbial living artefacts. To this aim, we harnessed material qualities in our design of a *Living Cyanobacteria Artefact*. This artefact served the dual purpose of indicating the well-being of the microbe and offering diverse performance possibilities, allowing for versatile positioning to support both its function (i.e., air purification) and well-being. Subsequently, we conducted a two-week in-situ study with eight participants with diverse caretaking experiences for other-than-human living beings. This study not only showcases a potential method for crafting habitats tailored to accommodate cyanobacteria but also demonstrates its effectiveness in supporting longitudinal in-situ investigations involving these organisms within living artefacts.

Importantly, this study stands as the first known longitudinal exploration involving cyanobacteria, offering valuable insights into their unique temporal patterns and behaviours within domestic settings. Furthermore, our work illuminates the pivotal role of materiality in the care of microbial living artefacts and highlights its performative potential as an important catalyst for HCI designers seeking to develop creative care approaches specifically tailored to these living artefacts. Our findings indicate that materiality can be harnessed to: 1) *increase habitat resilience for supporting care labour*; 2) *surface livingness for enhancing care knowledge* and 3) *tune performativity for eliciting exploratory care*. Additionally, our research uncovers important dimensions that emerge in the design of care for living artefacts, notably between: 1) *temporal dissonance and temporal alignment*; 2) *familiar and unfamiliar living aesthetics*; and 3) *exploratory and prescriptive practices of care*. In conclusion, we call for HCI designers to give substantial consideration to aspects of temporality, openness, mutualism, and multidimensionality when approaching the design of care for living artefacts.

REFERNCES

[1] J. Zhou, Z. Doubrovski, E. Giaccardi, and E. Karana. “Living with Cyanobacteria: Exploring Materiality in Caring for Microbes in Everyday Life”. In: *Proceedings of the CHI Conference on Human Factors in Computing Systems*. CHI ’24. Honolulu, HI, USA: Association for Computing Machinery, 2024. ISBN: 9798400703300. DOI: 10.1145/3613904.3642039. URL: https://doi.org/10.1145/3613904.3642039.

[2] M. P. de la Bellacasa. *Matters of Care: Speculative Ethics in More than Human Worlds.* Minneapolis: University of Minnesota Press, 2017. ISBN: 9781517900656. URL: http://www.jstor.org/stable/10.5749/j. ctt1mmfspt (visited on 05/17/2023).

[3] K. Helms and Y. Fernaeus. “Troubling Care: Four Orientations for Wickedness in Design”. In: *Proceedings of the 2021 ACM Designing Interactive Systems Conference.* DIS ’21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 789–801. ISBN: 9781450384766. DOI: 10.1145/3461778.3462025. URL: https://doi.org/10.1145/3461778.3462025.

[4] N. Campo Woytuk, J. Y. Park, J. Maslik, M. Ciolfi Felice, and M. Balaam. “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/10.1145/3563657.3595966.

[5] D. J. Haraway. *The companion species manifesto: Dogs, people, and significant otherness*. Vol. 1. Chicago, the United States: Prickly Paradigm Press Chicago, 2003.

[6] F. Aspling, J. Wang, and O. Juhlin. “Plant-computer interaction, beauty and dissemination”. In: *ACM International Conference Proceeding Series* 15-17-Nove (2016). DOI: 10.1145/2995257.2995393.185

[7] M. Chang, C. Shen, A. Maheshwari, A. Danielescu, and L. Yao. “Patterns and Opportunities for the Design of Human-Plant Interaction”. In: *Designing Interactive Systems Conference*. DIS ’22. Virtual Event, Australia: Association for Computing Machinery, 2022, pp. 925–948. ISBN: 9781450393584. DOI: 10.1145/3532106.3533555. URL: https://doi.org/10.1145/3532106.3533555.

[8] C. Mancini, J. van der Linden, G. Kortuem, G. Dewsbury, D. Mills, and P. Boyden. “UbiComp for Animal Welfare: Envisioning Smart Environments for Kenneled Dogs”. In: *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing.* UbiComp ’14. Seattle, Washington: Association for Computing Machinery, 2014, pp. 117–128. ISBN: 9781450329682. DOI: 10.1145/2632048.2632073. URL: https: //doi.org/10.1145/2632048.2632073.

[9] Y. Ikeya, R. Wakkary, and B. Barati. “Metamorphonic: A Reflective Design Inquiry into Human-Silkworm Relationship”. In: *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. DIS ’23. Pittsburgh, PA, USA: Association for Computing Machinery, 2023, pp. 808–819. ISBN: 9781450398930. DOI: 10 .1145 /3563657 .3596053. URL: https:

//doi.org/10.1145/3563657.3596053.

[10] R. Wakkary, D. Oogjes, N. Sakib, and A. Behzad. “Turner Boxes and Bees: From Ambivalence to Diffraction”. In: *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. DIS ’23. Pittsburgh, PA, USA: Association for Computing Machinery, 2023, pp. 790–807. ISBN: 9781450398930. DOI: 10.1145/3563657.3596081. URL: https://doi.org/10.1145/3563657.3596081.

[11] M. Haldrup, K. Samson, and T. Laurien. “Designing for Multispecies Commons: Ecologies and Collaborations in Participatory Design”. In: *Proceedings of the Participatory Design Conference 2022* - Volume 2. PDC ’22. Newcastle upon Tyne, United Kingdom: Association for Computing Machinery, 2022, pp. 14–19. ISBN: 9781450396813. DOI: 10.1145/3537797.3537801. URL: https://doi.org/10.1145/3537797.3537801.

[12] R. Armstrong. “Biodesign for a culture of life: Of microbes, ethics, and design”. In: *Lockton, D., Lenzi, S., Hekkert, P., Oak, A., Sádaba, J., Lloyd, P. (eds.) Spain: DRS2022: Bilbao, 2022*, pp. 1–20. DOI: 10.21606/drs.2022.144. URL: https://doi.org/10.21606/drs.2022.144.

[13] F. Bell, M. Ramsahoye, J. Coffie, J. Tung, and M. Alistar. “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/10.1145/3563657.3596133.

[14] K. J. Locey and J. T. Lennon. “Scaling laws predict global microbial diversity”. In: *Proceedings of the National Academy of Sciences* 113.21 (2016), pp. 5970–5975. DOI: 10.1073/pnas.1521291113. eprint: https: //www.pnas.org/doi/pdf/10.1073/pnas.1521291113. URL: https: //www.pnas.org/doi/abs/10.1073/pnas.1521291113.

[15] R. Cavicchioli, W. J. Ripple, K. N. Timmis, F. Azam, L. R. Bakken, M. Baylis, M. J. Behrenfeld, A. Boetius, P. W. Boyd, A. T. Classen, and et al. “Scientists’ warning to humanity: Microorganisms and climate change”. In: *Nature Reviews Microbiology* 17.9 (2019), pp. 569–586. DOI: 10.1038/s41579-019-0222-5.

[16] R. Kim, P. Pataranutaporn, J. Forman, S. A. Lee, I. H. Riedel-Kruse, M. Alistar, E. S. Lazaro Vasquez, K. Vega, R. van Dierendonck, G. Gome, O. Zuckerman, A. Vujic, D. S. Kong, P. Maes, H. Ishii, M. Sra, and S. Poslad. “Microbe-HCI: Introduction and Directions for Growth”. 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: 10.1145/3411763.3450408. URL: https://doi.org/10.1145/3411763.3450408.

[17] T. Merritt, F. Hamidi, M. Alistar, and M. DeMenezes. “Living media interfaces: a multi-perspective analysis of biological materials for interaction”. In: *Digital Creativity* 31.1 (2020), pp. 1–21. ISSN: 17443806. DOI: 10.1080/14626268. 2019.1707231.

[18] B. Barati, E. Karana, S. Pont, and T. van Dortmont. “Living Light Interfaces —an Exploration of Bioluminescence Aesthetics”. In: *Designing Interactive Systems Conference 2021.* DIS ’21. Virtual Event, USA: Association for Computing Machinery, 2021, pp.

1215–1229. ISBN: 9781450384766. DOI: 10.1145/3461778.3462038. URL: https://doi.org/10.1145/3461778.3462038.

[19] E. G. Groutars, C. C. Risseeuw, C. Ingham, R. Hamidjaja, W. S. Elkhuizen, S. C. Pont, and E. Karana. "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*. CHI '22. New Orleans, LA, USA: Association for Computing Machinery, 2022. ISBN: 9781450391573. DOI: 10.1145/3491102.3517713. URL: https: //doi.org/10.1145/3491102.3517713.

[20] N. Ofer, F. Bell, and M. Alistar. "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.

[21] J. Zhou, R. Kim, Z. Doubrovski, J. Martins, E. Giaccardi, and E. Karana. "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/10.1145/3563657.3596132.

[22] A. D. Cheok, R. T. Kok, C. Tan, O. N. N. Fernando, T. Merritt, and J. Y. P. Sen. "Empathetic living media". In: *Proceedings of the Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques*, DIS. 2008. ISBN: 9781605580029. DOI: 10.1145/1394445.1394495.

[23] R. Kim, C. Risseeuw, E. G. Groutars, and E. Karana. "Surfacing Livingness in Microbial Displays: A Design Taxonomy for HCI". 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 .3581417. URL: https: //doi.org/10.1145/3544548.3581417.

[24] G. Oktay, Y. Ikeya, M. Lee, B. Barati, Y. Lee, Y. Chen, L. Pschetz, and C. Ramirez-Figueroa. "Designing with the More-than-Human: Temporalities of Thinking with Care". In: *Companion Publication of the 2023 ACM Designing Interactive Systems Conference*. DIS '23 Companion. Pittsburgh, PA, USA: Association for Computing Machinery, 2023, pp. 104–106. ISBN: 9781450398985. DOI: 10 .1145 /3563703 .3591462. URL: https: //doi.org/10.1145/3563703.3591462.

[25] J. Liu, D. Byrne, and L. Devendorf. "Design for collaborative survival: An inquiry into human-fungi relationships". In: *Conference on Human Factors in Computing Systems - Proceedings* 2018-April (2018). DOI: 10.1145/3173574.3173614.

[26] D. Chen, Y. a. Seong, H. Ogura, Y. Mitani, N. Sekiya, and K. Moriya. "Nukabot: Design of Care for Human-Microbe Relationships". 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: 10.1145/3411763.3451605. URL: https: //doi.org/10.1145/3411763.3451605.

[27] J. Lu and P. Lopes. “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/10.1145/3526113. 3545629.

[28] E. Karana, B. Barati, and E. Giaccardi. “Living Artefacts: Conceptualizing Livingness as a Material Quality in Everyday Artefacts.” In: *International Journal of Design* 14.3 (2020), pp. 37–53. URL: http://www.ijdesign.org/ index.php/IJDesign/article/view/3957/923.

[29] E. Giaccardi and E. Karana. “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.

[30] E. Karana, E. Giaccardi, N. Stamhuis, and J. Goossensen. “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.

[31] F. Hamidi and M. Baljko. “Rafigh: An Edible Living Media Installation”. In: *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction.* TEI ’14. Munich, Germany: Association for Computing Machinery, 2014, pp. 345–346. ISBN: 9781450326353. DOI: 10.1145/2540930. 2555209. URL: https://doi.org/10.1145/2540930.2555209.

[32] R. Kim, S. Thomas, R. van Dierendonck, and S. Poslad. “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*. FDG ’18. Malmö, Sweden: Association for Computing Machinery, 2018. ISBN: 9781450365710. DOI: 10.1145/3235765.3235798. URL: https://doi.org/10.1145/3235765.3235798.

[33] S. A. Lee, E. Bumbacher, A. M. Chung, N. Cira, B. Walker, J. Y. Park, B. Starr, P. Blikstein, and I. H. Riedel-Kruse. “Trap It! A Playful Human- Biology Interaction for a Museum Installation”. 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. 2593–2602. ISBN: 9781450331456. DOI: 10.1145/2702123.2702220. URL: https://doi.org/10.1145/2702123.2702220.

[34] E. Frier and J. Douenias. Living Things. Frier and Douenias. 2015. URL: http://www.ethanfrier.com/living-things.

[35] ecologicStudio. AirBubble by ecoLogiStudio for Otrivin Breathe Clean. ecologicStudio. 2021. URL: https://www.ecologicstudio.com/projects/ airbubble-playground-and-exhibition.

[36] R. Aghighi. Biogarmentry: Photosynthetic Living textile for an alternative every-

day. Material Incubator. n.d. URL: https://www.materialincubator. com/biogarmentry.

[37] J. Hahn. Bio-ID Lab designs DIY algae-infused tiles that can extract toxic dyes from water. Dezeen. 2019. URL: https://www.dezeen.com/2019/09/21/bio- id-lab-indus-algae-tiles-water/.

[38] L. Giraud. Installation Algaegraphique. Giraud. 2014. URL: http://www. liagiraud.com/cultures/.

[39] M. Sawa, A. Fantuzzi, P. Bombelli, C. J. Howe, K. Hellgardt, and P. J. Nixon. "Electricity generation from digitally printed cyanobacteria". In: *Nature communications* 8.1 (2017), pp. 1–10.

[40] G. C. Cannon, C. E. Bradburne, H. C. Aldrich, S. H. Baker, S. Heinhorst, and J. M. Shively. "Microcompartments in prokaryotes: carboxysomes and related polyhedra". In: *Applied and environmental microbiology* 67.12 (2001), pp. 5351–5361.

[41] T. Sun, Y. Zhang, C. Zhang, H. Wang, H. Pan, J. Liu, Z. Li, L. Chen, J. Chang, and W. Zhang. "Cyanobacteria-based bio-oxygen pump promoting hypoxia-resistant photodynamic therapy". In: *Frontiers in bioengineering and biotechnology* 8 (2020), p. 237.

[42] D. Datta, E. L. Weiss, D. Wangpraseurt, E. Hild, S. Chen, J. W. Golden, S. S. Golden, and J. K. Pokorski. "Phenotypically Complex Living Materials Containing Engineered Cyanobacteria". In: *bioRxiv* (2023), pp. 2023–01.

[43] I. Jang, J. Park, Y. Son, J. Min, W. Park, and C. Yi. "Photosynthetic living building material: Effect of the initial population of cyanobacteria on fixation of CO2 and mechanical properties". In: *Construction and Building Materials* 396 (2023), p. 132218.

[44] K. Schipper, M. Al Muraikhi, G. S. H. Alghasal, I. Saadaoui, T. Bounnit, R. Rasheed, T. Dalgamouni, H. M. S. Al Jabri, R. H. Wijffels, and M. J. Barbosa. "Potential of novel desert microalgae and cyanobacteria for commercial applications and CO 2 sequestration". In: *Journal of Applied Phycology* 31 (2019), pp. 2231–2243.

[45] J. C. Tronto. *Moral Boundaries: A Political Argument for an Ethic of Care*. New York, NY: Routledge, 1993.

[46] M. Murphy. "Unsettling care: Troubling transnational itineraries of care in feminist health practices". In: *Social Studies of Science* 45.5 (2015), pp. 717–737. ISSN: 03063127. URL: http://www.jstor.org/stable/43829053 (visited on 09/12/2023).

[47] C. Key, C. Gatehouse, and N. Taylor. "Feminist Care in the Anthropocene: Packing and Unpacking Tensions in Posthumanist HCI". In: *Proceedings of the 2022 ACM Designing Interactive Systems Conference*. DIS '22. Virtual Event, Australia: Association for Computing Machinery, 2022, pp. 677–692. ISBN: 9781450393584. DOI: 10.1145/3532106.3533540. URL: https://doi.org/10.1145/3532106.3533540.

[48] J. Bardzell, S. Bardzell, and A. Light. "Wanting To Live Here: Design After Anthropocentric Functionalism". 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: 10.1145/3411764.3445167. URL: https://doi.

org/10.1145/3411764. 3445167.

[49] R. Wakkary. *Things we could design: For more than human-centered worlds*. Cambridge, MA: MIT press, 2021.

[50] C. Key, F. Browne, N. Taylor, and J. Rogers. “Proceed with Care: Reimagining Home IoT Through a Care Perspective”. 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 .3445602. URL: https: //doi. org/10.1145/3411764.3445602.

[51] D. Easterly, M. Kenyon, and T. Rorke. “Tardigotchi: Considerations on Pets and Digital Simulations”. In: *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’11. Easterly. Funchal, Portugal: Association for Computing Machinery, 2010, pp. 391–392. ISBN: 9781450304788. DOI: 10.1145/1935701.1935795. URL: https://doi.org/10.1145/1935701.1935795.

[52] H. Jung and E. Stolterman. “Digital Form and Materiality: Propositions for a New Approach to Interaction Design Research”. In: *Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design*. NordiCHI ’12. Copenhagen, Denmark: Association for Computing Machinery, 2012, pp. 645–654. ISBN: 9781450314824. DOI: 10.1145/2399016. 2399115. URL: https://doi.org/10.1145/2399016.2399115.

[53] S. Gross, J. Bardzell, and S. Bardzell. “Structures, forms, and stuff: the materiality and medium of interaction”. In: *Personal and Ubiquitous Computing* 18 (2014), pp. 637–649.

[54] M. Wiberg, H. Ishii, P. Dourish, A. Vallgårda, T. Kerridge, P. Sundström, D. Rosner, and M. Rolston. “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.

[55] A. Vallgårda and J. Redström. “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.

[56] D. K. Rosner, M. Ikemiya, D. Kim, and K. Koch. “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.

[57] B. Barati, E. Giaccardi, and E. Karana. “The Making of Performativity in Designing [with] Smart Material Composites”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI ’18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–11. ISBN: 9781450356206. DOI: 10.1145/3173574.3173579. URL: https://doi.org/10.1145/3173574.3173579.

[58] C. Zhong, R. Wakkary, W. Odom, A. Y. S. Chen, M. Yoo, and D. Oogjes. “On the Design of DeformTable: Attending to Temporality and Materiality for Supporting Everyday Interactions with a Shape-Changing Artifact”. In: *Proceedings of the 2022 ACM Designing*

Interactive Systems Conference. DIS ’22. Virtual Event, Australia: Association for Computing Machinery, 2022, pp. 1555–1564. ISBN: 9781450393584. DOI: 10.1145/3532106.3533501. URL: https://doi.org/10.1145/3532106.3533501.

[59] R. Braidotti. “Posthuman humanities”. In: *European Educational Research Journal* 12.1 (2013), pp. 1–19.

[60] E. Giaccardi. “Casting things as partners in design: towards a more-than- human design practice”. In: *Relating to Things: Design, Technology and the Artificial*. Ed. by H. Wiltse. Bloomsbury, 2020. Chap. 6, pp. 99–132. DOI: 10.5040/9781350124288.ch-006.

[61] P. J. Stappers and E. Giaccardi. “Research through design”. In: *The encyclopedia of human-computer interaction*. The Interaction Design Foundation, 2017, pp. 1–94.

[62] E. Karana, B. Barati, V. Rognoli, A. Zeeuw Van Der Laan, et al. “Material driven design (MDD): A method to design for material experiences”. In: *International Journal of Design* 9.2 (2015), pp. 35–54.

[63] S. Parisi, V. Rognoli, and M. Sonneveld. “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. URL: https://doi.org/10.1080/14606925.2017.1353059.

[64] C. Li, Q. He, Y. Wang, Z. Wang, Z. Wang, R. Annapooranan, M. I. Latz, and S. Cai. “Highly robust and soft biohybrid mechanoluminescence for optical signaling and illumination”. In: *Nature Communications* 13.1 (2022), p. 3914. DOI: 10.1038/s41467-022-31705-6.

[65] A. Konopka and T. D. Brock. “Effect of temperature on blue-green algae (cyanobacteria) in Lake Mendota”. In: *Applied and environmental microbiology* 36.4 (1978), pp. 572–576.

[66] P. Sengers and B. Gaver. “Staying Open to Interpretation: Engaging Multiple Meanings in Design and Evaluation”. In: *Proceedings of the 6th Conference on Designing Interactive Systems*. DIS ’06. University Park, PA, USA: Association for Computing Machinery, 2006, pp. 99–108. ISBN: 1595933670. DOI: 10.1145/1142405.1142422. URL: https: //doi.org/10.1145/1142405.1142422.

[67] V. Braun and V. Clarke. “Using thematic analysis in psychology”. In: *Qualitative Research in Psychology* 3.2 (2006), pp. 77–101. DOI: 10.1191/ 1478088706qp063oa. URL: https://www.tandfonline.com/doi/abs/10. 1191/1478088706qp063oa.

[68] W. W. Gaver, J. Bowers, A. Boucher, H. Gellerson, S. Pennington, A. Schmidt, A. Steed, N. Villars, and B. Walker. “The Drift Table: Designing for Ludic Engagement”. In: *CHI ’04 Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’04. Vienna, Austria: Association for Computing Machinery, 2004, pp. 885–900. ISBN: 1581137036. DOI: 10.1145/985921.985947. URL: https://doi.org/10.1145/985921.985947.

[69] P. Pons and J. Jaen. “Designing Interspecies Playful Interactions: Studying Children Perceptions of Games with Animals”. In: *Proceedings of the Fourth International Conference on Animal-Computer Interaction*. ACI ’17. Milton Keynes, United Kingdom: Association for

Computing Machinery, 2017. ISBN: 9781450353649. DOI: 10.1145/3152130.3152139. URL: https: //doi.org/10.1145/3152130.3152139.

[70] F. French, I. Hirskyj-Douglas, and H. Väätäjä. “Designing Technologies for Playful Interspecies Communication”. In: *Proceedings of the Seventh International Conference on Animal-Computer Interaction*. ACI ’20. Milton Keynes, United Kingdom: Association for Computing Machinery, 2021. ISBN: 9781450375740. DOI: 10 .1145 /3446002 .3446003. URL: https: //doi.org/10.1145/3446002.3446003.

[71] G. Shakeri, F. Jung, F. Altarriba Bertran, A. Friday, and D. Fernández Galeote. “Eco-Joy: Imagining Sustainable and Joyful Food Eco-Label Futures”. In: *Adjunct Proceedings of the 2022 Nordic Human-Computer Interaction Conference*. NordiCHI ’22. Aarhus, Denmark: Association for Computing Machinery, 2022. ISBN: 9781450394482. DOI: 10.1145/3547522.3547694. URL: https://doi.org/10.1145/3547522.3547694.

[72] F. Altarriba Bertran, O. ’. Buruk, V. Spors, and J. Hamari. “Playful Inspiration for a New Wave of Joyful Forest Technology”. In: *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. DIS ’23. Pittsburgh, PA, USA: Association for Computing Machinery, 2023, pp. 1886–1903. ISBN: 9781450398930. DOI: 10 .1145 /3563657 .3596015. URL: https: //doi.org/10.1145/3563657.3596015.

[73] E. Karana, H. McQuillan, V. Rognoli, and E. Giaccardi. “Living artefacts for regenerative ecologies”. In: *Research Directions: Biotechnology Design* 1 (2023), e16. DOI: 10.1017/btd.2023.10.

[74] L. Yao, J. Ou, C.-Y. Cheng, H. Steiner, W. Wang, G. Wang, and H. Ishii. “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.

[75] H. Jain, K. Lu, and L. Yao. “Hydrogel-Based DIY Underwater Morphing Artifacts: A Morphing and Fabrication Technique to Democratize the Creation of Controllable Morphing 3D Underwater Structures with Low- Cost, Easily Available Hydrogel Beads Adhered to a Substrate.” In: *Proceedings of the 2021 ACM Designing Interactive Systems Conference*. DIS ’21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 1242–1252. ISBN: 9781450384766. DOI: 10.1145/3461778.3462136. URL: https://doi.org/10.1145/3461778.3462136.

[76] R. Kim, S. Thomas, R. van Dierendonck, N. Bryan-Kinns, and S. Poslad. “Working with Nature’s Lag: Initial Design Lessons for Slow Biotic Games”. In: *International Conference on the Foundations of Digital Games*. FDG ’20. Bugibba, Malta: Association for Computing Machinery, 2020. ISBN: 9781450388078. DOI: 10.1145/3402942.3409790. URL: https: //doi.org/10.1145/3402942.3409790.

[77] F. Bell, N. Ofer, E. Frier, E. McQuaid, H. Choi, and M. Alistar. “Biomaterial Playground: Engaging with Bio-Based Materiality”. In: *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI EA ’22. New Orleans, LA, USA: Association for Computing Machinery, 2022. ISBN: 9781450391566. DOI: 10.1145/3491101.3519875. URL:

https://doi.org/10.1145/3491101.3519875.

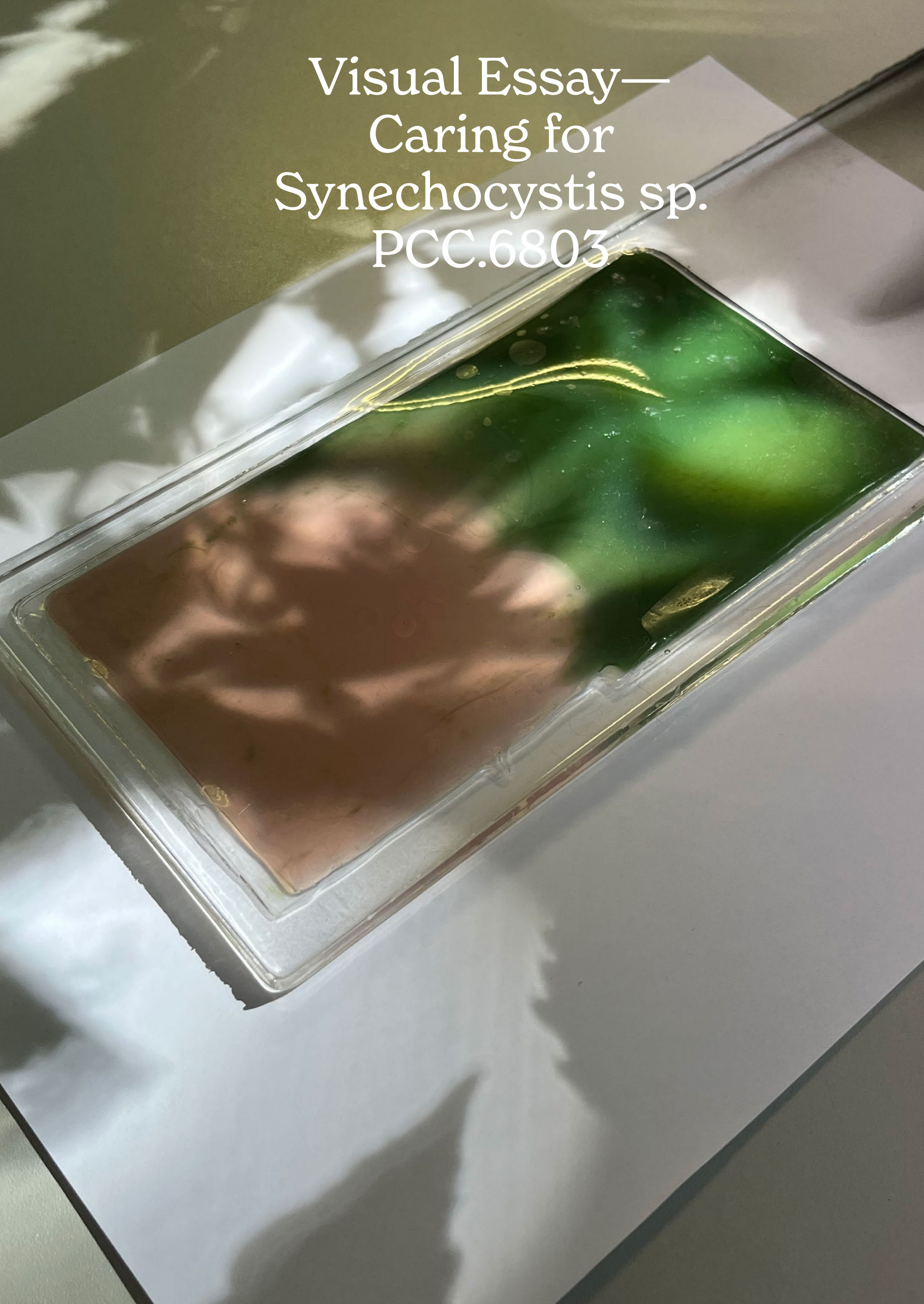
[78] E. Giaccardi and J. Redström. “Technology and more-than-human design”. In: *Design Issues* 36.4 (2020), pp. 33–44.

[79] M. Kitazaki, I. Nicenboim, E. Giaccardi, L. Kuijer, L. Neven, and B. Lopez. “Connected Resources: A Research through Design approach to designing for older people’s resourcefulness”. In: *Proceedings of the 2019 Research through Design Conference*. RTD ’19. 2019. DOI: 10.6084/m9.figshare.7855868.v2.

[80] E. Giaccardi and I. Nicenboim. Resourceful Ageing: Empowering Older People to Age Resourcefully with the Internet of Things. Original work published 2018. Delft, NL: TU Delft OPEN Publishing, 2023. DOI: 10.59490/mg.76. URL: https://doi.org/10.59490/mg.76.

[81] E. Giaccardi, C. Speed, N. Cila, and M. L. Caldwell. “Things as Co-Ethnographers: Implications of a Thing Perspective for Design and Anthropology”. In: *Design anthropological futures*. Bloomsbury Academic, 2016.

Visual Essay—
Caring for
Synechocystis sp.
PCC.6803



Pilot Study: Living with "Lucy"

The first day living with "Lucy" marked a vibrant and subtle purple hue arising in the middle of the light green.

Lucy hiding under the shadow of a
sunlight-loving house plant, shying away from direct
sunlight that shone onto both.

Oxy.

Not long after the first encounter, oxy had definetely transformed.

Oxy in the garden—
breathing alongside other beings,
sharing the soft light
and late spring breeze.


Pulse

Overtime, Oxy had deepened its green hue, expanding its body, whilst the purple gradually disappeared, losing its sensitivity.

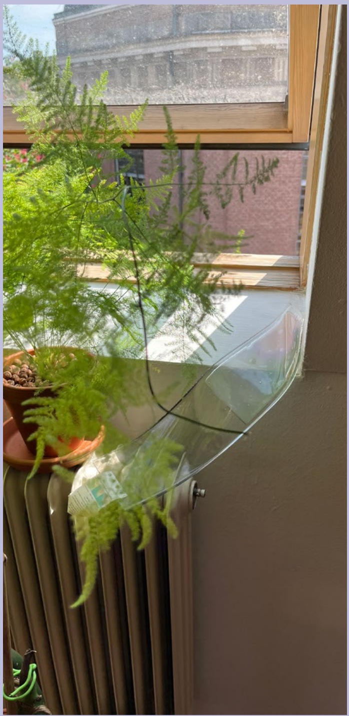
Nezuko.

In the quiet rhythm of shared living, Nezuko found her place—suspended in gentle conformity with the contours of furniture, lingering softly near her human co-habitant.

Jun Jun.

Soon after arrival, Jun Jun showed a delightful vibrant purple hue.

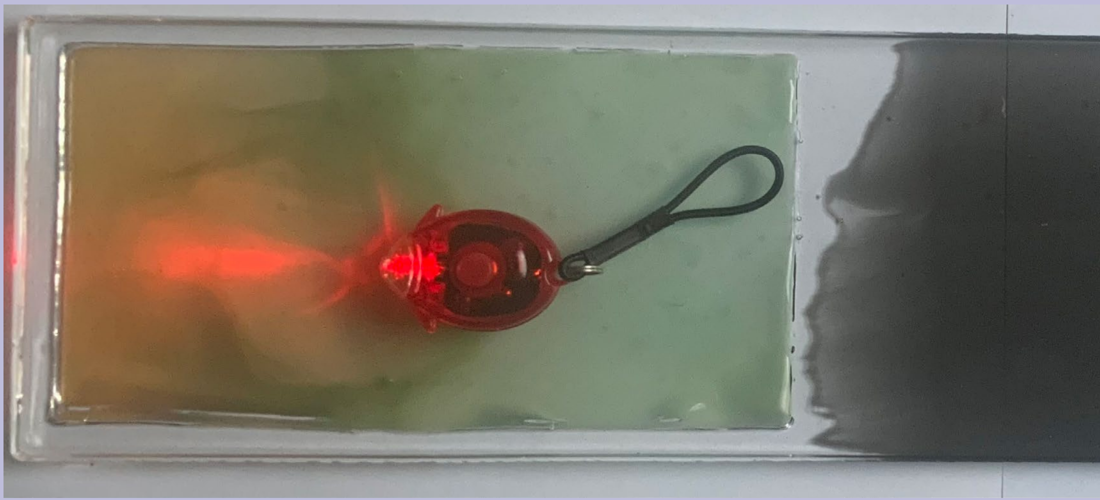


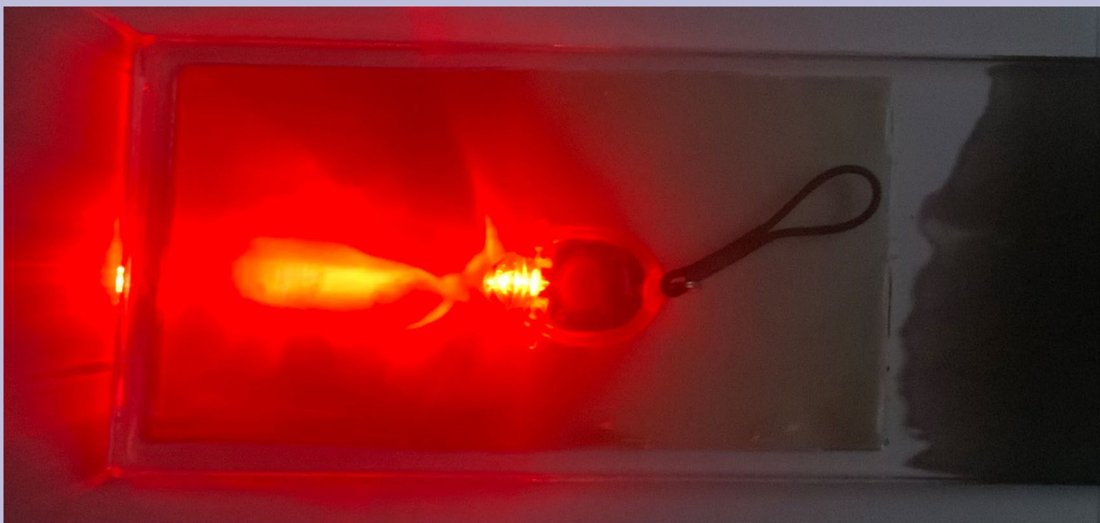


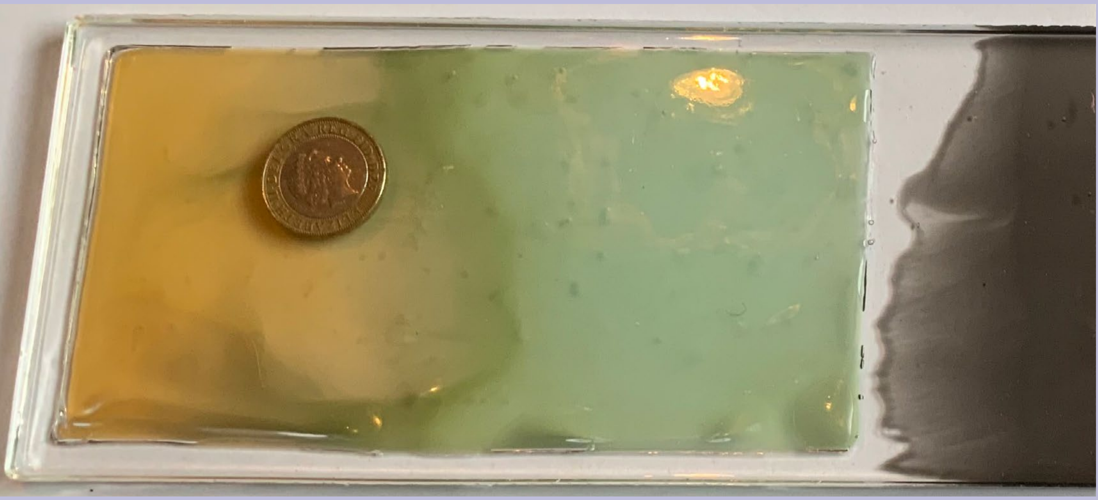

Untitled I.

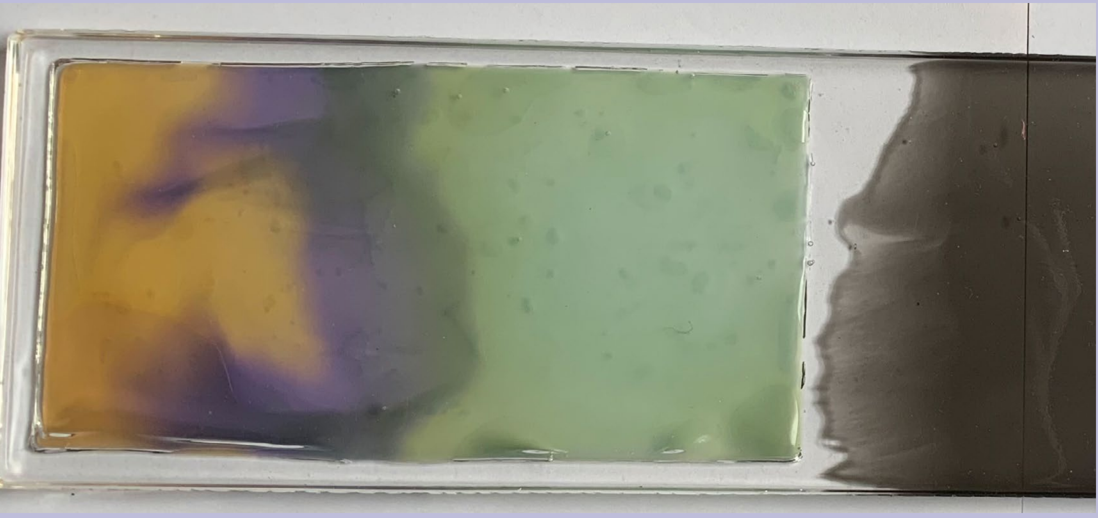
One morning, a participant shared a sunlit breakfast—quietly accompanied by the artefact, as if part of the ritual.

Patient hands, guided by scientific curiosity, tended the artefact—diligent experiments unfolding under the gaze of a microbiologist.

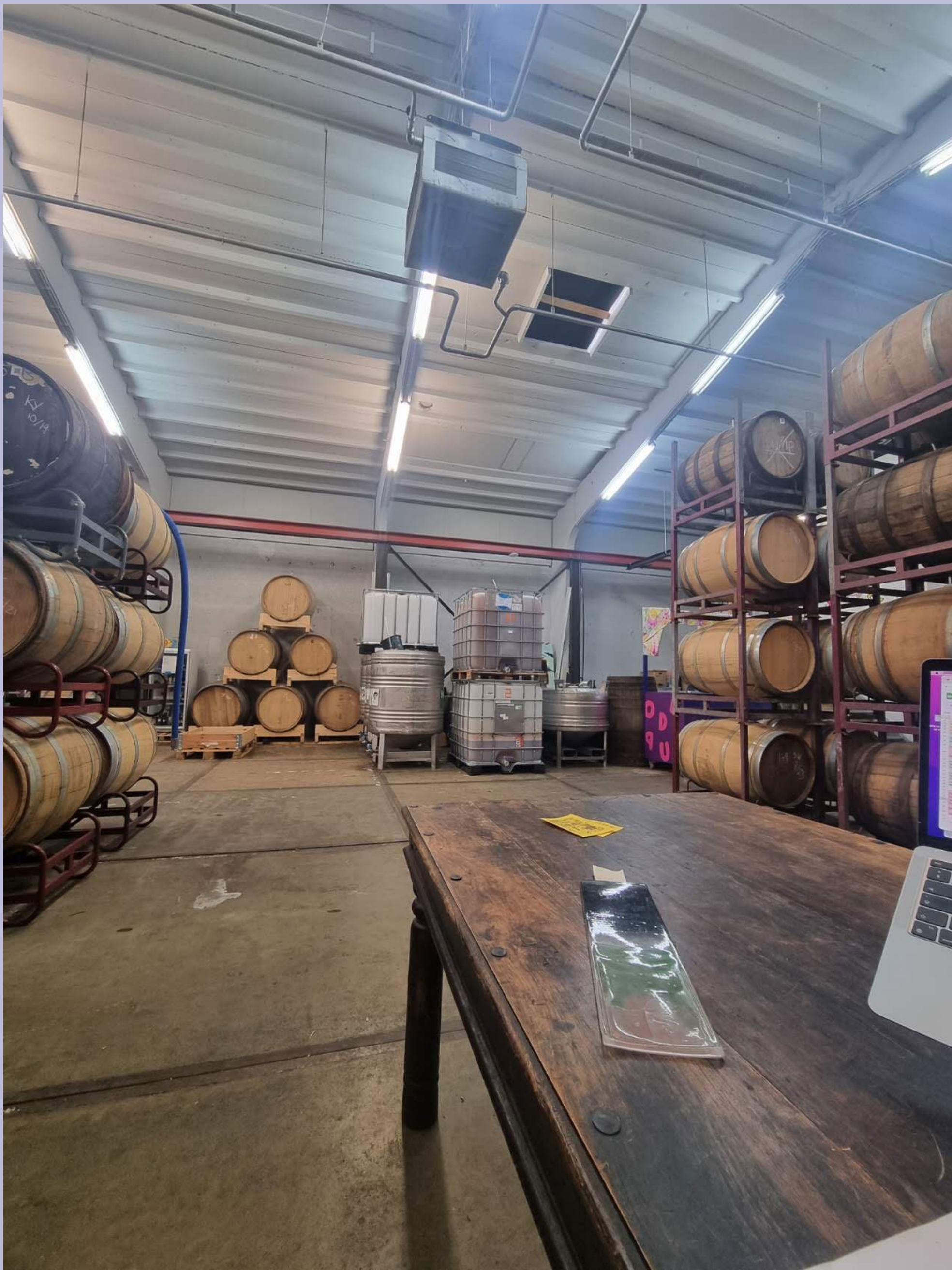








Untitled II.



The artefact found its way into a brewery,
nestled in the thick breath of fermentation,
amist the yeast and scent of hops.


KY
10/14
10/18

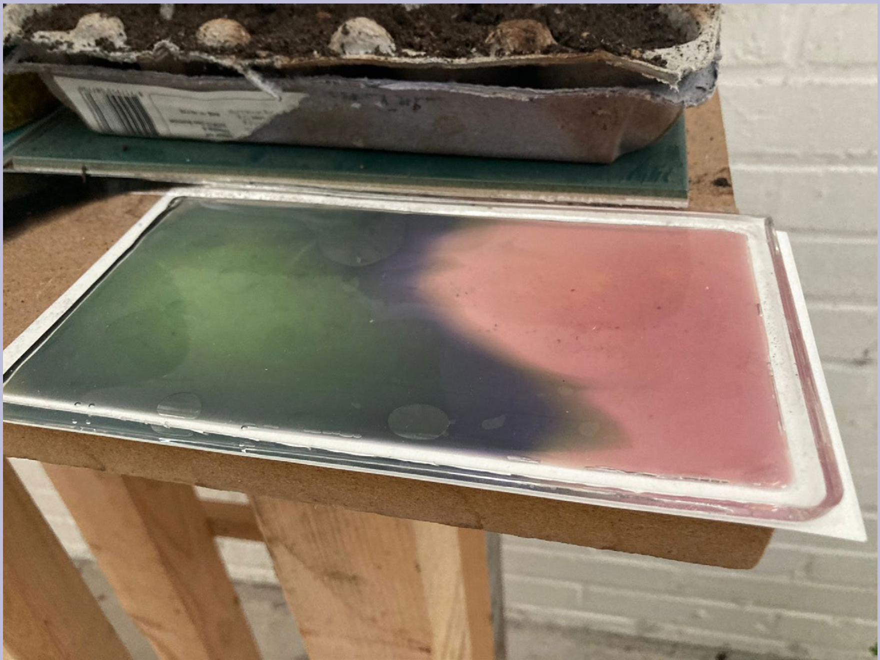
Noticing its fading hue,
a gentle light was offered through the night—
a quiet gesture of care.

Nicky.

In the soft shade of the household,
it was uncertain
whether Nicky could endure.

To our surprise,
it revived after thought
being “dead” weeks after the study,
and forming uniquely a texture of life
and tenaciousness.

Untitled III.

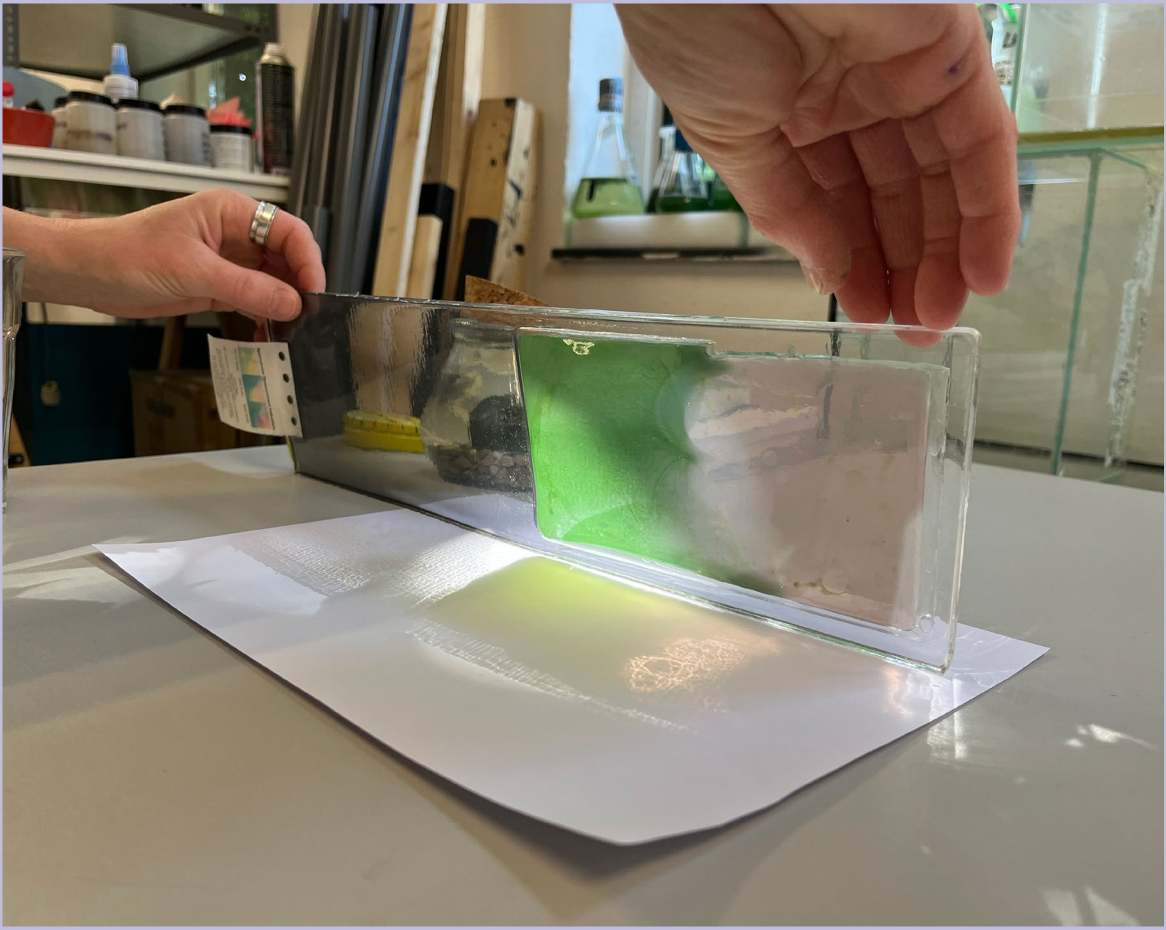


"Let it do its own thing."

Positioned with care, the artefact rested
within sight of the bedroom window—
a silent companion in daily passing.

Hoopla!


REST!



Through cycles of trial and error, Hoopla
gradually unfolded into its most beautiful
hue by the study's end, with a peaceful tone.

6 Discussion and Reflection

"Both kinship and ethical accountability need to be redefined in such a way as to rethink links of affectivity and responsibility not only for non-anthropomorphic organic others, but also for those technologically mediated, newly patented creatures we are sharing our planet with."

—Rosi Braidotti

The final chapter synthesizes the implications of my research contributions for biodesigners and the broader design communities engaged in designing care with and for living organisms. It begins by revisiting the research questions, offering a comprehensive summary of how they interrelate and have been addressed across the chapters of the dissertation. The chapter then outlines and discusses my contributions, categorized into three key pillars: Theoretical and Conceptual Contributions, Empirical and Experiential Insights and Methodological Contributions. Following this, I critically reflect on my research methodology, particularly the integration of research-through- design, material-driven design, and the balance between theory and practice. These reflections highlight the iterative, intuitive, and hands-on nature of my approach while addressing its alignment with the interdisciplinary and relational goals of biodesign. Finally, I discuss the practical, epistemological and ethical ambivalences encountered throughout the research process, and explore ways of navigating these ambivalences. In the end, I discuss the limiations of this reserach and suggest future work.

6.1. ADDRESSING RESEARCH QUESITIONS

This dissertation has explored and addressed three research questions which accumulate in the programmatic Research-through-Design process. Below, I summarize their interrelations, and key findings of each question.

6.1.1. HOW CAN WE CRAFT THE SHARED HABITATS OF HUMAN AND LIVING ARTEFACTS FOR THEIR MUTUAL WELL-BEING?

This question lies at the heart of designing with multispecies relationality and fostering multispecies flourishing in biodesign. It reflects the overarching goal of "more-than-human care" and is addressed across Chapters 3, 4, and 5 of this dissertation.

The dissertation introduces the *biodesign continuum* framework (Chapter 3), offering biodesigners a structured approach to engage with multispecies relationality. This framework comprises three interconnected pillars that span the temporal phases of design and cohabitation:

Understanding the Habitat: Focuses on identifying and analyzing the ecological and relational dynamics within natural or artificial habitats. This understanding is foundational to creating optimal assemblages that support the living organisms integral to biodesign.

Embodying the Habitat: Involves the physical and material realization of habitats designed to promote the thriving of living organisms, referred to as the "first habitat" [1]. These form the basis for creating shared multispecies habitats (the "second habitat")[1].

Perpetuating the Habitat: Centers on the long-term sustenance of shared habitats, ensuring that living organisms and humans thrive together. This pillar emphasizes both the biological maintenance of living organisms and the social practices that sustain their care relations.

Each pillar addresses a distinct yet interconnected dimension of designing living artefacts, guiding biodesigners towards meaningful engagement with multispecies cohabitation. Together, these pillars advocate for the continuous configuration and reconfiguration of habitats throughout the lifespan of living artefacts.

Technologies for Crafting Shared Habitats

Chapter 3 highlights the growing importance of digital tools in the biodesign continuum through a taxonomy of these technologies. These tools are particularly vital in perpetuating shared habitats, as they facilitate multispecies communication, making the well-being states of living organisms perceptible to humans. This is especially significant for microorganisms that may be imperceptible or exhibit metabolic changes too subtle to detect in real time.

Gaps, Opportunities, Challenges and Tensions

The dissertation also identifies notable gaps and challenges in achieving mutual well-being within shared habitats:

A Gap of Materiality: Chapter 3 points out the under-explored potential of dynamic materials, direct material engagement, encompassed by the overarching lens of materiality in crafting care relations in the shared habitat of humans and living artefacts.

Challenge of Human-Microbe Temporal Dissonance: Care for microorganisms presents unique challenges to timely care due to their unique temporalities, which demand innovative approaches to enable reciprocal relationships.

Prescriptive and Static Care Instructions: Care practices often rely on prescriptive guidance, which may fail to accommodate the unpredictable and dynamic realities of living with living artefacts. These gaps inform the subsequent research questions addressed in Chapters 4 and 5.

In conclusion, the dissertation contends that fostering mutual well-being within shared habitats requires an in-depth understanding of the relational dynamics between humans and living artefacts. It advocates for the deliberate crafting of these entangled ecological and social relationships through the thoughtful configurations of the habitat. The dynamic interplay between materiality and human practices is pivotal in enabling the habitat to adapt and evolve continuously toward a state of mutual flourishing. To achieve this, designers must actively engage with emerging technologies that integrate the strengths of both digital and physical realms. By leveraging these tools, they can cultivate and sustain the relationships within shared habitats, guided by a biodesign framework that encompasses understanding, embodying, and perpetuating the habitat. This approach underscores the critical role of design in nurturing multispecies thriving in biodesign.

6.1.2. HOW CAN WE DESIGN WITH TEMPORAL DISSONANCE TO FOSTER RECIPROCAL RELATIONSHIPS BETWEEN HUMAN AND LIVING ARTEFACTS?

This question explores the gaps surrounding dynamic materials and the challenges posed by microbial temporality in care relationships, primarily addressed in Chapters 4 and 5. Building on insights from the first research question, the dissertation identifies the unique temporalities of microbes in biodesign and introduces the concept of temporal dissonance. Temporal dissonance refers to the time lag humans experience in noticing the metabolic changes of certain microbes—a design challenge that can hinder timely care but also a generative opportunity for fostering reciprocal relationships between humans and living artefacts.

Addressing and Designing with Temporal Dissonance

To address temporal dissonance, the dissertation presents two living artefacts that employ dynamic material interfaces to facilitate human noticing and care for microbes:

Cyano-chromic Interface (Chapter 4): This artefact leverages an electrochromic material composite to visually manifest cyanobacteria's photosynthetic activity as a monochromatic display. The interface serves as a foundational building block for living artefacts in diverse contexts. Through the design of four imaginary artefacts built on the Cyano-chromic Interface, the dissertation explores potential interactions and reciprocal relationships between humans and microbes. These speculative designs expand the imaginative space of human-microbe cohabitation and illustrate how dynamic materials can prompt humans to notice and respond to microbial living states.

Living Cyanobacteria Artefact (Chapter 5): This artefact incorporates a pH-indicating substance to display cyanobacteria's photosynthetic activity through a visible color change occurring over several hours. A longitudinal study with this artefact demonstrated how such interfaces can enhance care knowledge by making the living states and temporalities of microbes more perceptible. The study provides empirical evidence that dynamic material interfaces not only support the vitality of living artefacts but also encourage human actions that actively reconfigure shared habitats to foster reciprocity.

In conclusion, through these explorations, the dissertation critically examines the generative potential of designing with temporal dissonance in biodesign. It advocates not only for aligning human-microbe temporalities to facilitate care but also for recognizing and embracing the meaningful dissonance inherent in their interactions. Designing with temporal dissonance can cultivate a deeper sensibility toward microbial life in and through living artefacts, fostering reciprocal relationships that go beyond mere care maintenance to engage with the rich diversity of multispecies temporalities with affection and appreciation.

6.1.3. HOW CAN WE FOSTER THE CREATIVE UNFOLDING OF CARE PRACTICES TOWARDS LIVING ARTEFACTS IN EVERYDAY LIFE?

This question explores the challenge identified in the first research question, focusing on how materiality and dynamic, non-prescriptive approaches to care can accommodate the unpredictable and evolving relations with living with artefacts in the everyday. This inquiry is addressed in Chapter 5.

Designing a Temporal-aligning, Performative and Multi-situated Living Artefact

The dissertation builds on the premise that the materiality of artefacts plays a crucial role in shaping daily practices, particularly through their performative qualities. It demonstrates that this capacity can foster the creative and organic unfolding of care practices for living artefacts. To explore this potential, I designed the *Living Cyanobacteria Artefact*, which integrates air-purifying functionality with dynamic material properties, such as color-changing, pliability, adhesiveness, and suspendability. These qualities allow individuals to situate the artefact in diverse locations within domestic spaces, based on where air purification is needed and lighting conditions are optimal for the artefact's vitality.

Insights from the Longitudinal Study

A longitudinal study involving this artefact revealed key roles of materiality in nurturing care practices in creative and non-linear ways:

Increasing Habitat Resilience to Support Care Labour: Materiality can support the artefact's viability and can flexibly adjust care labour by making the artefact resilient to various environmental conditions and care requirements.

Surfacing Livingness to Enhance Care Knowledge: Temporal qualities of materials, such as colour-change, deepens knowledge of the artefact's well-being and shapes affection and appreciation.

Tuning Performativity to Elicit Exploratory Care: The artefact's performative material qualities invite exploratory and intuitive placement and attachment, encouraging individuals to creatively navigate both its functional role and the well-being of the embedded microbes.

These roles collectively enable the spontaneous and exploratory unfolding of care practices that challenge anthropocentric norms, fostering reciprocal relationships with living artefacts for multispecies flourishing.

Design Dimensions for Creative Care Practices

The dissertation identifies key design dimensions to consider when fostering creatively evolving care practices: 1) *Temporal Dissonance vs. Temporal Alignment*, 2) *Familiar vs. Unfamiliar Living Aesthetics* and 3) *Exploratory vs. Prescriptive Practices of Care*. These dimensions have been discussed extensively in Chapter 5, and will be further unpacked in the next section.

In conclusion, the dissertation calls for designers to give significant consideration to material qualities and design dimensions such as living aesthetics, temporalities, open-endedness, mutualism, and multidimensionality of care when designing for the creative unfolding of care practices for living artefacts that align with the complexity of both living systems and everyday life.

6.2. DISCUSSION OF CONTRIBUTIONS

My dissertation contributes to the ongoing scholarly discussion of matters of care in more-than-human worlds [2–7], specifically within the context of biodesign [1, 8–10]. The dissertation makes several contributions for design research concerning cohabitation with living artefacts. These contributions fall under three distinctive themes: 1) Theoretical and Conceptual Contributions: Expanding the Biodesign Discourse, 2) Empirical and Experiential Insights: Understanding Care Practices and Material Relations, and 3) Methodological Contributions: Practical Guidelines for More-than-Human Care in Biodesign. The following sections unpack each theme and contribution.

6.2.1. THEORETICAL AND CONCEPTUAL CONTRIBUTIONS: EXPANDING MORE-THAN-HUMAN DISCOURSE IN AND THROUGH BIODESIGN

Proposal of "Mattering More-than-human Care" in Biodesign

This dissertation advances the discourse on more-than-human care in biodesign by building on concepts such as *mutualistic care* [1] and *mutual thriving* [8], while offering a more nuanced perspective on care as a transformative and relational process. Drawing from feminist ethics of care, it conceptualizes care as a dynamic, ongoing negotiation mediated by material engagement in the complexities of everyday life [2, 11]. In this framework, care gains significance—or "comes to matter"—through the interplay of discursive and material practices [12].

This dissertation foregrounds materiality as a critical and generative space for designing care in cohabitation with living artefacts. It advocates for biodesign approaches that seamlessly invite and nurture care practices through the materiality of living artefacts. Rather than reinforcing a divide between digital and material realms, it embraces their increasingly blurred boundaries and mutual interplay. For instance, the electrochromic (EC) material explored in Chapter 4 exemplifies idea, as it operates at the intersection of electronic and non-electronic systems, responding to "electrons" that reflect the materiality of the digital world.

This work identifies two key facets of material dynamics that shape care relationships: *temporality* and *performativity*. Temporality emphasizes the diverse rhythms of humans, living organisms, and materials within an assemblage and how these temporalities interact to influence more-than-human relations. It highlights the potential for designs to align, juxtapose, or negotiate these temporalities through materials to foster mutual understanding and well-being. Performativity recognizes the agency of more-than-human entities in shaping human actions and practices in dynamic, evolving ways. It underscores the potential of materials to elicit exploratory, improvisational, and situated care practices.

Through design explorations and artefacts, this dissertation demonstrates how crafting the temporal and performative qualities of materials can foster care as a material-discursive phenomenon [12]. These practices exemplify how designers can "matter" care—imbuing it with versatility, creativity, situated knowledge, and haptic engagement—towards more-than-human entities mobilized in biodesign (Chapter 4 and 5). These contributions align with values championed by posthumanist and feminist STS scholars such as Donna Haraway and Maria Puig de la Bellacasa.

This work calls on biodesigners and design researchers to further investigate the intersections of materiality, care, and multispecies relations. It offers actionable frameworks and methodologies for designing artefacts that support relational, dynamic, and materially grounded care practices.

Framework of Biodesign Continuum in Crafting Habitabilities

My dissertation provides a framework of biodesign continuum in crafting habitabilities for biodesigners (Chapter 3). The biodesign continuum includes three interconnected and interdependent pillars: understanding the habitat, embodying the habitat and perpetuating the habitat.

The framework highlights a fundamental multispecies relationality in biodesign rooted in the shared habitat between the human and the living artefact, and in needs of mutual well-being. It expands the understanding of "habitabilities" as "abilities of things to condition livingness" [1], to *ongoing configurations of things to condition both physical and social interconnectedness and interdependency between living entities for multispecies flourishing*.

The framework also emphasizes a close link between knowing and doing, understanding and designing, responding to both Barad's and Puig de la Bellacasa's propositions of the constant interrelations among knowing, relating to and (care) doings [2, 13]. It rethinks designing living artefacts as an ongoing configuration and reconfiguration process, which blurs the boundaries between the design time and the time of cohabitation, between the designer to the cohabitant. It also emphasizes that the cohabitants "become with" each other through constant co-constructions within the shared habitat [2, 11]. In this process, the human develops more-than-human sensibilities towards the diverse needs and ecological principles, and the metabolic intricacies of their companion organism [9].

On a practical level, the framework serves as a guide for biodesigners crafting habitabilities. Designers may begin with any of the three pillars—*understanding, embodying, or perpetuating*—engaging in either learning-by-doing or doing-by-learning. Ultimately, the framework helps biodesigners identify missing links in their practice, encouraging a comprehensive approach that considers not only the physical but also the social, ecological, and ethical dimensions of living artefacts.

Concept of Temporal Dissonance

The dissertation introduces a strong concept [14] of *temporal dissonance* (Chapter 4), which highlights the "time lag" humans experience when perceiving the gradual metabolic changes of certain microbes [15, 16] in contexts of living artefacts where microbes are integrated into human everyday environments, and where their unique capabilities are appropriated to serve particular functions, such as cyanobacteria discussed in this research. I have articulated the dual consequences of temporal dissonance to biodesign: 1) offering opportunities for "slow technology" [17–19] and temporal design [20] as a generative design space for noticing other-than-human temporalities 2) posing a critical challenge for people to perform care for microbes hindered by noticing of their living states in a timely manner.

Attempting to address the challenge, and "sharpen human abilities to notice and engage with more-than-human temporalities" [21], I have demonstrated how *designing with temporal dissonance* can support biodesigners in fostering human–microbe reciprocity in and through cohabitation with living artefacts. Such alignment is not meant to synchronize human and microbial time as opposed by Puig de la Bellacasa [2], nor to emphasize that human and microbial time are inherently separate. It is meant to highlight a need for humans to recognize and bridge our cognitive dissonance in relating to other species' temporalities for understanding their living states. I focused on how "living aesthetics" [1] of cyanobacteria could be augmented (not replaced) by other materials, therefore become more perceivable by humans. The dissertation presents mainly two methods (Chapters 4 and 5) to do so, with variant degrees of alignment.

The dissertation argues that designing with temporal dissonance, such as aligning and juxaposing, can foster reciprocal relationships between humans and certain microbes within and through living artefacts. This has been explored through four speculative concepts in Chapter 4: Daylight Log, Kids' Hiking Companion, Circadian Navigator, and Mushroom Shade. Here I reiterate on how they shed light upon reciprocal human-microbe relationship for biodesigners from various perspectives. Daylight Log shows that the juxtaposition of aligned and dissonant temporalities in a living artefact is meaningful for humans to care for the microbe effectively and but still appreciate its slowness. Kids' Hiking Companion considers how temporal alignment might cultivate a sense of "shared vitality" [22, 23] between humans and the microbe. Circadian Navigator delves into the role of aligning temporal dissonance in fostering the achievement of a shared goal between the human and the microbe. Finally, Mushroom Shade imagines how temporal alignment can foster careful management of shared habitat elements between the human, the microbe and other living organisms in the environment.

These concepts have shown how biodesigners can meaningfully engage with temporal dissonance and its alignment, not as an inhibitor, but an enabler of alternative human-microbe reciprocity, such as shown particularly by Daylight Log. The fluidity in designing with both dissonance and alignment offers a multiplicity of pathways to Puig de la Bellacasa's theoretical proposition against recovering a sense of temporal oneness, and for fine-tuning our attentiveness to the rhythms of the "other" and the specific relational dynamics at play [2]. This concept also helps to raise critical questions such as: when and how is a slowly-responsive living artefact that reflect other temporalities meaningful? When and how is a temporal-aligned (to humans) living artefact meaningful? These questions are further unpacked through Chapter 5, which proposes a design dimension of temporal dissonance versus alignment for designers to navigate through different species and scenarios.

6.2.2. EMPIRICAL AND EXPERIENTIAL INSIGHTS: UNDERSTANDING CARE PRACTICES AND MATERIAL ENTANGLEMENTS

Understanding of the Role of Material Qualities in Nurturing More-than-human Care

This dissertation presents the first longitudinal study to date that explores how material qualities of living artefacts nurture care practices in everyday domestic contexts. The empirical findings of the role of material qualities include: *enhancing habitat resilience to support care labor, surfacing livingness to enhance care knowledge, and tuning performativity for eliciting exploratory care.* Chapter 5 has extensively discussed these roles and their associated design dimensions. Here I reiterate these insights by elaborating further on their theoretical engagement and application to broader contexts.

1. Enhancing habitat resilience to support care labour.

This finding reveals a close link between physical composition of habitats and required extent of care labour, which is a fundamental layer of care by definition of Puig de la Bellacasa's [2]. It offers an understanding of labour and work involved in more-than-human care as tunable and subjective. This means by tuning habitat materials and configurations, designers can calibrate the degree of human involvement in maintaining the vitality of living organisms according to specific contexts. For instance, design towards self-sustaining habitats (e.g., in Caravel [24]) enables more autonomous care systems, for engaging people in care actions on a minimum level. This might be suitable for public contexts such as urban environments. On the other hand, to establish a stronger personal bond with the living organism, designers may consider semi-open habitat structures foster direct, dynamic, and socially rich interactions, inviting people to engage in propagation and social exchange—such as some existing plant practices of sharing cuttings. This can be applied in care settings with a stronger educational purpose, such as education for environmental citizenship [25]. Although this is considered to be a common pattern, yet the study observed that the perception of care labour is subjective, and highly dependent on the individual's experiences, knowledge and skills. Whilst a life-long gardener found a living artefact easy to take care of, and anticipating more complicated care engagement, a "plant killer" struggled to even fulfill the basics.

2.Surfacing livingness for enhancing care knowledge.

This finding offers an empirical basis on how material semantics and temporal qualities can make "livingness" perceptible as a form of more-than-human care knowledge. This framing responds to Maria Puig de la Bellacasa's exploration of "knowing-caring" [2] and Tronto's "competence" as a key element of care ethics [26]. "Surfacing livingness" is a notion put forward by Kim et al. [15] in the context of designing microbial displays in human-computer interaction. Kim et al. offered design strategies to surface livingness of microbes, to foster the ability to recognize, interpret, and respond to microorganisms. As the artefact design reflects a form of "translating" strategy, which in a non-anthropocentric essence means "figuring out what the microbe is trying to say" [15]. From a temporality perspective, this insight has also validated in-situ that timely care can be facilitated through certain level of temporal alignment presented by Chapter 4. Such temporal engagement within materiality crafting has clearly driven the making of "care time" [2] from individuals.

Within this role, I have drawn attention to two important design dimensions in Chapter 5: temporal alignment vs dissonance, semantic familiarity vs unfamiliarity.

1) *Temporal dissonance and alignment*. Validating hypothesis in Chapter 4, a spectrum between temporal alignment and dissonance clearly shapes care practices. Temporal alignment facilitates more responsive, urgent care, and shortens the time of care learning, suitable for vulnerable species or context where urgent care is needed. For example, cyanobacteria-based living artefacts, which should avoid exposure to direct sunlight. Retaining certain temporal dissonance, on the contrary, fosters long-term engagement and appreciation of other-than-human temporalities, applicable in resilient species and relatively stable and mild conditions. Yet, designers may also consider combination of diverse temporalities for more complex scenarios.

2) *Semantic familiarity and unfamiliarty of livingness*. Familiar material semantics can amplify perceptions of livingness, enhancing care motivation. This is suitable for living organisms that presents semantic challenges, such as moldy microbes that have a negative association, and some microbes that show

a non-living like appearance indifferent to human perception [15]. Designers may consider "packaging" these microbes with the shape, form and motion of familiar living things. However, excessive familiarity risks animistic interpretations [27], ignores the unique living aesthetics of the living organism, and limit space for open interpretation. This dimension suggests a need for balance between familiarity and ambiguity to sustain poetic, performative representations of livingness.

3.Tuning Performativity for Eliciting Exploratory Care.

This role demonstrates that performative qualities of materials can elicit exploratory care practices that eventually evolve into established, habitual routines. This finding aligns with views of materiality as a transformative force in shaping social practices [12, 28]. Under this role, a third design dimension emerges. High ambiguity in form introduces uncertainty in how to care, risking critical functions and the well-being of vulnerable species. Striking the right balance between open-endedness and specified guidance through form could facilitate people to be creative towards microbes' care practices and to understand their diverse needs, scales, agencies, and temporalities [9], while learning about the dynamic and unpredictable nature of living systems.

This finding extends the discourse on open-ended design into the realm of more-than-human care. Open-endedness, as a widely embraced approach in design research, supports organically evolving human-technology relationships [29–32]. Concepts such as resourcefulness [33, 34], improvisation [33], appropriation [31], and reconfigurations [35] highlight the value of open-ended designs in fostering adaptability, creativity, and the emergence of new social norms. I argue that open-ended living artefacts invite humans to engage with other-than-human entities in ways that are ethically and creatively open to the "becoming" of unintended interactions. This approach emphasizes multispecies reciprocity [9] and response-ability [11].

Empirical Insights on Mutualistic Care

This dissertation contributes to biodesign by identifying and outlining a set of challenges in caring for microbes in everyday life: 1) temporal dissonance between the human and the microbe, 2) insufficiency of care instructions in supporting organically evolving care practices, and 3) fostering a sense of mutualistic care. The first two challenges have been addressed under other contribution discussions. Here, I mainly extend the discussion of the third challenge with empirical insights, fostering a sense of mutualistic care.

Mutualism is one of the four primary motivations and approaches to caring for the artefact in everyday contexts, uncovered by the longitudinal study in Chapter 5, among other motivations: livingness, curiosity toward new life forms, mutualism, and joyful interactions. However, mutualistic care was also the least realized and perceived. Participants often experienced a disconnect between their care practices and the artefact's functional use. Actions benefiting the artefact, such as exposing it to optimal lighting for photosynthesis, were often at odds with actions that benefited the participants, such as using the artefact for air purification in less ideal lighting conditions.

This misalignment is specific to the organism and its functional dependencies. In the case of cyanobacteria, light is both critical for the organism's survival and for triggering its functionality for humans. This creates a challenge when the intended location of "use" can only offer unsatisfactory "care," as observed in the beer brewer's case (Chapter 5). By contrast, bioluminescent dinoflagellates demonstrate a different dynamic: while light sustains their overall well-being during the day, it does not directly trigger their glow at night. Here, care at one time benefits the organism's well-being and its functional appeal later, fostering a more aligned relationship. The cyanobacteria example underscores the inherent difficulty of achieving a mutualistic relationship where human and microbial needs are simultaneously fulfilled.

The research identifies this disconnect as being deeply tied to how living artefacts are often conceptualized with singular, predefined functions. By prioritizing functionality, designers may inadvertently constrain the potential for humans to reinterpret or co-create what the artefact becomes through their interactions and relations.

To address this challenge, the dissertation calls on biodesigners to explore ways in bridging the gap between functionality and care, shifting away from singular functionality toward designs that allow mutualistic care relationships to evolve organically. This approach integrates living systems more deeply into everyday practices while repositioning the central focus of biodesign. By positioning mutualistic care as a central principle, this contribution challenges anthropocentric notions of functionality and promotes a multiplicity of understandings of "mutuality."

Technical and Experiential Understanding of Designing with Cyanobacteria

This dissertation bridges scientific and designerly perspectives to offer both technical and experiential insights into working with cyanobacteria for biodesign.

This integration is achieved through a material-driven design method that emphasizes technical understanding, experiential knowledge, and creative material tinkering processes [36].

Technical Insights The research solidifies hypotheses on engaging with cyano-bac- teria's unique temporalities and surfacing their livingness through iterative tinkering and experimentation. In particular, quantitative data on the performance of the *Cyano-chromic Interface*, detailed in Chapter 4, grounds the design conceptualiza- tion. This data not only validates the design but also facilitates the replication of experiments for further exploration by researchers and practitioners.

Experiential Insights The study also provides practical and experiential knowledge about cyanobacteria's distinct temporal patterns and behaviors within domestic settings (Chapter 3 and 5). These insights offer biodesigners guidance on integrating cyanobacteria into similar contexts, fostering nuanced understanding that align with everyday environments.

By combining these two perspectives, the dissertation supports the design community with a holistic understanding of a cyanobacteria as a starting point for more design explorations with them, fostering a plurality of human-cyanobacteria relationships.

6.2.3. METHODOLOGICAL CONTRIBUTIONS: PRACTICAL GUIDELINES FOR MORE-THAN-HUMAN CARE IN AND THROUGH BIODESIGN

Taxonomy of Digital Tools in Crafting Habitabilities

This dissertation introduces a taxonomy outlining the roles of digital tools in crafting habitabilities for living artefacts, framed within the biodesign continuum. The taxonomy encompasses key applications of digital technologies that support habitat design, including:

Observing and Recording: Monitoring environmental and biological conditions.

Modeling and Simulating: Visualizing and predicting habitat dynamics.

Fabricating the Scaffold: Designing and constructing physical frameworks for living artefacts.

Depositing Cells and Chemicals: Precisely placing biological and chemical elements.

Form-Finding: Enabling optimal habitat conditions.

Interfacing Multispecies: Facilitating communication of living states between humans and other-than-human species.

Regulating the Habitat: Adjusting environmental parameters to maintain habitat conditions.

For each role, the taxonomy provides case-specific practical insights to guide biodesign practices that prioritize mutual well-being between humans and living organisms. By doing so, it not only highlights existing applications but also identifies opportunities for appropriating or advancing current digital tools.

The taxonomy encourages the development of novel digital tools to address complex biodesign scenarios. For instance, it suggests exploring tools for empathetic interfaces that deepen the relational understanding between humans and living artefacts, fostering care relations. Additionally, it offers a framework for biodesigners and researchers to contextualize and position digital tools within their specific projects, enhancing the alignment of tools with design objectives and multispecies needs.

Guidelines of Designing Temporal-aligning Living Interfaces

This dissertation outlines two methods for designing temporal aligning living artefacts, demonstrated through the development of the *Cyano-chromic Interface* (Chapter 4) and the *Living Cyanobacteria Artefact* (Chapter 5).

The Cyano-chromic Interface deploys electrochromic (EC) materials to manifest the changes in photosynthetic activity of cyanobacteria within the time frame of a few minutes. The Living Cyanobacteria Artefact uses a PH-indicating solution to do so within the time frame of a few hours. They both shorten the time for humans to notice cyanobacteria's photosynthetic activities significantly, yet with a varying degree of alignment. Besides, the Cyano-chromic Interface examines the customization of interfaces as modular building blocks adaptable to various scenarios. A design space of such customization has been provided. Such flexibility underscores the situatedness of materiality [2], encouraging biodesigners to engage with the fluid, context-sensitive nature of material interactions.

These approaches serve as both methodological inspiration and a technical entry point for designers interested in bridging human and more-than-human temporalities to foster reciprocal relationships. Here I point out a few key deliberate design decisions made for both methods with an anti-anthropocentric essence [15]:

1) Respecting Native Expression. The interface utilizes cyanobacteria's inherent expression of livingness—color change—without translating microbial signals into unrelated modalities like sound or light. This approach respects the agency of cyanobacteria by preserving their unique manifestations of life. It contrasts with alternative strategies, such as those used in the Bio-Digital Calendar, which translates kombucha growth signals into auditory outputs [37].

2) Juxtaposing Diverse Temporalities. Both interfaces retains both fast and slow color changes, reflecting microbial temporal rhythms alongside human-perceivable changes. This design choice intentionally disrupts "productionist time" [2] as the only interpretation of temporality, resisting the urge to conceal microbial temporalities in favor of human convenience.

Compared to other methods oriented towards temporal attunement to more-than-human entities, the methods explored by this dissertation are relatively intrusive, which involve modification of the living organism's habitat conditions—from liquid to jelly. This aspect has been reflected upon in Chapter 4. This reflection highlights a spectrum ranging from direct interventions in microbial habitats (intrusive) to non-intrusive "listening" strategies, such as passively observing kombucha culture growth demonstrated in the Bio-Digital Calendar project [37].

Whilst encouraging designers to engage more with the living organisms' native expressions, the dissertation acknowledges the potential for power asymmetries inherent in more intrusive methods [21]. Designers are encouraged to critically reflect on their methods, asking: How can we attune to microbial temporalities in ways that honor their native expressions while acknowledging our power asymmetry?

Technique of Designing Microbial Living Artefact for Longitudinal Studies

Longitudinal studies offer valuable opportunities to explore the everyday, mundane, and evolving practices of more-than-human care. However, due to the relatively nascent integration of biological systems in design and the associated technical and practical challenges, such studies involving living artefacts are still rare. These challenges include creating reliable living artefacts capable of sustaining interaction over extended periods, maintaining the vitality of the organisms, and ensuring safety for human participants.

The Living Cyanobacteria Artefact presented in this dissertation marks the first in-situ, long-term study involving cyanobacteria (Chapter 5). This research provides a step-by-step methodology for crafting artefacts that can sustain themselves for at least a month. The approach can be adapted to work with other living organisms such as microalgae, bioluminescent bacteria or dinoflagellates, and flavobacteria, broadening its application for other biodesign contexts.

The practical deployment of this method also revealed several challenges, including unpredictable changes to the artefact over time, which can diminish its sensitivity and longevity. Designers should carefully account for these potential fluctuations, ensuring the artefact's resilience and adaptability to foster meaningful long-term interactions.

Techniques of Performative and Multi-situated Microbial Living Artefacts

This dissertation provides designers with step-by-step guide of creating performative and multi-situated microbial living artefacts. This allows the artefact to elicit actions or responses from people and adapt to various locations and configurations. This is a replicable and adaptable method for future projects.

Artefacts with performative and multi-situated qualities are versatile, suitable for deployment in both controlled or explorative studies. These artefacts facilitate diverse interactions between humans and living entities, encouraging participants to engage in real-time decision-making that considers the needs of cyanobacteria, their own needs, and habitat elements. These dynamic interactions can be studied for research questions around the dynamics, situatedness, and evolvement of practices with living artefacts which are open for unpredictability. The approach can be adapted to design artefacts involving other microbial species, such as microalgae, fungi, or flavobacteria.

6.3. REFLECTIONS

6.3.1. ON METHODOLOGY

Research through Design as a Methodological Anchor

Research through Design (RtD) has been an invaluable methodological anchor throughout my research journey, providing both structure and flexibility in navigating an emerging and rapidly evolving field. When I began my PhD in 2020, the academic discourse around designing living artefacts was in its infancy, with foundational work like the living artefacts framework only recently published.

Unlike fields rich with established theories and methodologies, this area offered few "shoulders to stand on," to borrow Isaac Newton's metaphor. Instead, I found myself standing at the edge of an expansive, uncharted landscape—an exhilarating but challenging position.

In such an emergent field, it is neither practical nor productive to begin with narrowly defined research questions aimed at filling specific knowledge gaps. Instead, RtD offered a dynamic and iterative process where questions could emerge organically, evolve over time, and lead to new avenues of inquiry. This methodological openness allowed me to embrace uncertainty while maintaining a reflective and purposeful approach to research.

Central to this process was the interplay between the research program—the overarching aims of my work—and the experiments—the iterative activities that continually shaped and refined those aims. This dynamic not only grounded my creative explorations but also provided a framework for critical reflection and adjustment. For instance, my initial interest in the potential of digital tools for crafting habitabilities gradually evolved into a deeper focus on material engagement and the role of materiality in cultivating care relations. This evolution was not a linear progression but a process of molding and kneading ideas through experimentation, reflection, and iteration.

Moreover, the RtD approach allowed me to integrate and hold together a multiplicity of methods, including first-person lived experiences, imaginary artefacts, material-driven design and longitudinal studies as was needed by specific stage. This methodological pluralism enriched my research, enabling also a multiplicity of perspectives in understanding the complexities of designing living artefacts and the care relationships they foster.

Looking back, RtD was not simply a tool for inquiry but an epistemological orientation that shaped my approach to research. It enabled me to engage with uncertainty not as an obstacle but as an opportunity for creative and critical inquiry in an emerging field.

Positioning in Theory-practice Spectrum

The research began with a review of literature and practices, which was later enriched by deeper theoretical engagement with posthumanism, feminist care ethics, and new materialism. This progression allowed me to leverage my designerly background, naturally grounded in practice, to explore design's potential contributions. Given biodesign's emerging nature and its relative lack of established theoretical foundations, engaging with broader Science and Technology Studies (STS) theories provided alternative intellectual frameworks, or "shoulders of giants," on which to build. These theoretical perspectives not only shaped my analytical lens but also helped articulate the rationale behind my decisions, fostering a dynamic interplay between theory and practice throughout the process. That said, this sequence is not the only path to addressing the research questions. One could also begin with a stronger initial engagement with theories, enabling conceptual "leaps" unconstrained by the boundaries of existing practices and technologies.

The intricate interplay between theories and practices is a generative space for novel research questions that span a wide spectrum. Yet, both theory and practice can become "rabbit holes" when approached without a clear consciousness; rather, their dynamic interplay is essential for advancing both the conceptual and applied dimensions of the field. As Nicenboim et al. note, the nomadic practices of designers [38], suggested by Wakkary, generate "situated, embodied, and partial forms of knowledge rather than adhering to an objectivist or universalist framework." [39] Similarly, as Giaccardi et al. suggest, "concepts are not given or handed over, they are continuously made and constantly remade. There is a crucial difference between thinking of theory as something we "just" apply in design, and thinking about theory as something we make use of in, and through, design." [40] This interplay underscores the importance of allowing theories and practices to inform one another iteratively, "establishing generative intersections between posthuman theory and more-than-human practices." [39]

Designerly and Scientific Ways of Knowing

The interplay between scientific and artistic modes of inquiry is a recurring theme throughout my dissertation. Chapter 4 briefly highlights the importance of balancing scientific grounding with imaginaries. This section delves deeper into how the dyanmics between scientific and designerly modes of knowing shape design research and practices involving living organisms, particularly through the lens of Material-Driven Design (MDD) [36].

Rooted in MDD, my research is inspired by its commitment to synergizing material science with designerly approaches to emphasize both functionality and experiences [36]. However, designing living artefacts demands deliberate decentering of human experiences as a goal, but instead, a heightened attention to certain more-than-human relations. And therefore, it requires designers to acknowledge and respect the different temporalities and needs of both humans and the living organism. For example, the unique biological and ecological processes of cyanobacteria, that require specific more-than-human sensibilities [9]. I approached cyanobacteria through both scientific and designerly ways.

Pollini's recent discussion on the designerly way of knowing in biodesign draws a distinction between the roles of a *biodesigner* and a *designer in lab* [41]. While the latter operates within the constraints of lab protocols and strict hygiene requirements—potentially limiting creative exploration—this role allows for deeper engagement with scientific knowledge, leveraging lab setups and interdisciplinary feedback to achieve sophisticated outcomes. Pollini envisions a field where biodesigners adopt diverse roles, from creative-expressive exploration to scientifically rigorous approaches, emphasizing lifelong learning as essential for these hybrid professionals [41]. She highlights the potential of designerly way of knowing to foster transdisciplinary collaborations and make meaningful contributions to scientific research [41].

While I question the necessity of drawing a strict divide between a biodesigner and a designer in lab—particularly as specialized biolabs dedicated to biodesign, such as the Biodesign Lab at TU Delft, continue to emerge—I strongly agree that scientific and designerly ways of knowing complement one another in biodesign research. Yet, there's not a single one way, but a diversity of ways. In my work, the designerly ways of knowing has been foundational, embodied through intentional methodological choices that embrace the non-linear, intuitive, reflective, and hands-on nature of design. My process involved personal lived experiences and material tinkering with living organisms, which not only revealed challenges and tensions in care relations with microbes but also allowed me to explore my own positionality in biodesign. This experiential approach provided opportunities to learn through making and to share this know-how with practitioners, contributing to a growing body of practice-based knowledge.

At the same time, my scientific ways of knowing extended beyond adherence to lab protocols and hygiene standards. I engaged critically with scientific literature (as was reflected in Chapter 4 about tacit knowledge), conducted controlled lab experiments, and actively participated in interdisciplinary dialogues. These activities equipped me with essential technical skills for interacting with living organisms, brought their ecological and biological contexts to the forefront, and lent plausibility to speculative design scenarios. This engagement expanded the designer's toolkit, enabling more effective interdisciplinary communication with experts in biology, ecology, and other fields.

I argue that balancing scientific and designerly approaches is crucial for cultivating a holistic understanding of the other-than-human entities we design with. This interplay aligns with science and technology studies (STS) perspectives, which advocate for viewing subjects not merely as "facts" but as "concerns" imbued with care [2, 42]. It is through this dynamic choreography that a deeper, more nuanced relationship with living organisms can emerge.

Ultimately, this dissertation advances an organism-specific approach to Material-Driven Design (MDD) within biodesign, particularly in fostering more-than-human care. Demonstrated by my engagement with cyanobacteria, it advocates for designs that are attuned to the expressions and rhythms of specific living organisms, promoting a respectful and responsive engagement that enriches the relational possibilities of biodesign; and situates more-than-human care in practices.

Workshop-based and Participatory Methods for Engaging Plurality of Voices

My research questions, predominantly focused on "how," have guided the inquiry with a practical orientation. This leaves great opportunity for future work to invite other critical perspectives: are there implicit assumptions underpinning these questions that have not been adequately scrutinized? Consider, for instance, aspects such as power asymmetry and politics of care.

To address these issues, future research could consider adopting workshop-based methodologies [43, 44] and emerging participatory approaches, particularly those engaging with more-than-human perspectives [45–47]. If given more time, I would like to discuss my generated conceptual artefacts in multiple stages of my research with diverse experts and stakeholders. These include other biodesigners, biologists, ecologists, more-than-human design researchers, caregivers, and even the living organisms at the heart of the inquiry—to collaboratively examine how power and politics are embodied in these artefacts. I would like to situate these discussions within lived contexts of others and engaging with the practices and priorities of others to surface assumptions, broaden perspectives, and enrich the research with a multiplicity of voices and experiences.

6.3.2. STAYING WITH THE TROUBLE: REFLECTION UPON MY AMBIVALENCES

Positioned at the intersection of biodesign and more-than-human care, I have navigated ambivalences—defined as "psychological states in which a person holds mixed feelings (positive and negative) toward some psychological object"

[48](p. 123)—throughout my research. Some of these ambivalences emerged from pivotal moments and questions, often involving pauses, hesitations, or re-evaluations before certain decisions were made; others came to surface in retrospect. While these moments did not halt progress, they remain significant and merit foregrounding in this final discussion. By sharing these reflections, I aim to resonate with fellow researchers and open space for further inquiry. This section recounts key events, examines the ambivalences they evoked, and proposes directions for future design and research.

Practical Ambivalence in Selecting Sustainable Nonliving Materials

At the 2022 Design Research Society conference, we organized a Conversation session to explore the ethical, ecological, and practical challenges of designing with living artefacts [49]. Early in the discussion, a participant raised a question about sustainability and ethical concerns of designing artificial habitats for microbes. Specifically, they questioned whether it aligns with its sustainability aim to confine living organisms in non-biodegradable materials, such as a plastic box, even when the project claims creating sustainable benefits.

Though this question was not aimed directly at my work, it encapsulates a dilemma I also encountered in selecting materials for constructing my living artefacts. Ensuring bio-compatibility, bio-safety, and durability often necessitates using materials like glass, plastics, and silicone—inorganic substances that are typically non-biodegradable and reliant on complex recycling infrastructure. Besides, these materials may not be sustainably sourced, produced, or disposed of. Furthermore, extensive lab experimentation generates significant amounts of disposable waste, adding another layer to the sustainability question.

Additionally, one of my design experiments required the use of specific materials or composites which cannot be substituted by any more sustainable options. Creating Cyano-chromic Interface involved harnessing electrons from cyanobacteria which required specific conductive ink, which is not bio-based nor regenerative. This experiment also required an electro-chromic composite material to surface cyanobacteria's photosynthetic activity. The electro-chromic composite contains conductive PET sheets, a polymer mixture of two ionomers called poly (3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), and silver ink as the electrode material. Besides the sustainability concerns mentioned above, the composite itself does not support easy disassembly.

Overall, material selection and sourcing for designing the Cyano-chromic Interface had been a lengthy and sometimes frustrating process, as it involved many trials and errors with different materials which might also involved long waiting time, just to make the system work. To find ideal materials that also meet sustainability requirements remain challenging, if not impossible in my case. Considering the project time frame and publishing deadlines I had to meet, I did not delve into finding material alternatives.

As it is, biodesigners may continue to grapple with research reality and critically evaluate their choice of materials and consider the full life cycle of each component. Incorporating sustainability assessment tools, such as Life Cycle Assessment (LCA), could help designers better understand and mitigate the ecological impact of their designs. But I would like to bring such ambivalence to the front end in my future research, and further contribute by directing research toward reducing environmental impacts throughout biodesign process. This could include developing inorganic materials for living artefacts that are also biodegradable.

Epistemological Ambivalence in Not Knowing Microbes Sufficiently

In my research, I frequently use the terms of "well-being" or "thriving" when I talk about "living states" of living artefacts or microbes. For instance, one of my research questions asks, “How can we craft the shared habitat of humans and living artefacts to ensure their mutual well-being?” Initially, I started to use these terms based on the living artefacts framework, which states that temporal changes in a living material can indicate an organism’s “well-being or struggle” [1](p.46); and that mutualistic care is "a reciprocal and evolving relationship between humans and living artefacts, where humans act upon a living artefact in order for it to thrive." [1] (p.46)

However, when I initially introduced this term to biologists and lab technicians, I encountered significant resistance. For some, it seemed to challenge their expertise, sparking a need to dissect and clarify the concept before any further discussion. A language that seemed natural and intuitive to me, proved to be not taken for granted. And this disciplinary gap highlighted the need of "translating" such concepts across fields. As I delved more into scientific literature, I realized that microbial "well-being" or "thriving" lacks a shared definition across science and design. Whilst "well-being" of microbes is rarely mentioned or investigated in microbiology or ecology, ecological studies offer rich literature about microbial "thriving." They mainly focus on growth, reproduction and success in ecological competition [50–52]. Some emphasizes on other factors such as "metabolizing, maintaining cellular integrity and expressing division genes," as differentiating elements than merely "surviving" [51]. And these studies put emphasis on the thriving of microbial communities, rather than an individual cell [52].

In biodesign research, concepts like human-microbe mutual thriving (e.g., Armstrong's work [8]) and "mutualistic care" (e.g., Karana et al.'s framework [1]) often employ thriving or care metaphorically, emphasizing mutual relationships rather than absolute or quantitative values. Similarly, in my research, as discussed in Chapter 3, I focus on the mutuality of well-being and thriving, where living entities fulfill their metabolic needs, maintain vitality, and create a balanced, sustainable relationality. For instance, I interpreted photosynthetic activity not merely as a measure of air purification for humans but also as an indicator of cyanobacteria's living states, given that photosynthesis is crucial for their survival, growth, and reproduction. This approach does not aim to reduce the well-being of either humans or cyanobacteria to a single measurable factor but seeks, in the context of care relations, to initiate actionable experiments that inspire broader discussions.

Critics might argue that applying well-being to microbes risks anthropocentrism, as microbes may lack the physiological foundation for experiencing well-being. These debates ask whether we can transcend human perspectives to meaningfully discuss microbial well-being. I argue that, just because terms such as well-being might be a human projection, it doesn't make it anthropocentric. It is part of humanity that needs to be celebrated as we are emotionally abundant and able to empathize, respond to, and connect with with other species. For example, when I lived with the two microbes at the early stage of my research, it was my natural human empathy, and thinking with human languages what the microbes might be experiencing that built my bond and kinship with them (see, Chapter 3 and its accompanying visual essay). In human and dog relationships, which have been thoughtfully unfolded in *When Species Meet* [53], where humans emotional projections of love and loyalty foster empathy, care and companionship, which in turn influence how dogs behave and respond. This co-shaping creates mutual accountability and "response-ability" between species [53]. Haraway also advocates for responsible and reflexive projection, where humans remain aware of their limits and strive to understand the other species on their terms [53].

On the other hand, I think it's also not helpful to use these terms blindly. Rather, we should be aware of what we mean when we talk about well-being and thriving of other species. And diving into nuances, celebrating differences across disciplines and concerns is a precious quality of design research. I recognize the broader need to understand microbial well-being, which is unique to microbes' "agency and interests." [54] And I believe the first step begins with acknowledging they have interests and creating opportunities for them to express these [54]. Extending this openness to microbial life seems a natural step, even if our understanding remains incomplete. Thus, to navigate this ambivalence in biodesign and more-than-human care, I propose three perspectives:

First, we must acknowledge and embrace not-knowing of other life forms with humility [38] when designing with living organisms. By embracing not-knowing, I do not mean to let it be an excuse of not inquiring into it. Rather, this mindset encourages openness to the mysteries and uncertainties inherent in other life forms. Instead of striving for complete understanding and even control, design research can focus on creating environments that allow the natural behaviors and processes of microbes to emerge in an environment that's native to them as much as possible.

Second, perhaps instead of purely relying on facts to support research questions and design decisions, we should see facts as tools for imagining others in biodesign. One pioneering example is the research of plant scientist Monica Gagliano, which uses empirical research to support her philosophical inquiry into plant intelligence and memory, a controversial area that not every colleague of her is convinced about. But she demonstrates that imagination is essential in science for knowing more about living organisms—not just with our minds, but also with our hearts. She describes imagination as "opening the door" to new ways of understanding our world.

Following a similar path, in discussion of microbe well-being, my design experiment with the Cyano-chromic Interface used a scientific approach in biological experiments to ground my conceptual imaginations of human-microbe reciprocity. Although the effects shown through the proof of concept was subtle, and further studies are needed to showcase its full fledged potential, the proof of concept materializes a possibility for imagining alternative relationship with cyanobacteria. And this is my designerly interpretation from matters of facts, to matters of concern [42], and to matters of care [2].

Delightedly, attitudes toward imagination in science are evolving, with growing recognition of its role of achieving a deeper understanding of the world [55] in thought experiments, models, metaphors, and the exploration of theoretical ideas [56, 57].

Finally, I call on research stakeholders—funding bodies, reviewers, and others—to loosen the strict adherence to conventional evidence-based reasoning in designing for more-than-human worlds, and explore new ways of doing in the gray areas in-between factual knowledge and ideological pursuit. While empirical evidence remains important, over-reliance on it can stifle the creativity and ethics crucial to scholarship, especially in the context of climate change and planetary crisis. Techno-scientific research should embrace designerly way of knowing [41] that features the intuitive and creative design approach, beneficial when designers are involved in collaborations with scientific disciplines. But also include anecdotal, intuitive, indigenous and "gut" knowledge about other-than-human lives. And my dissertation strives to demonstrate some of the ways towards developing great sensibilities for cyanobacteria that are still highly tacit.

Ethical Ambivalence in Instrumentalizing/Intervening with Living Organisms

At the DRS conference, participants in our Conversation session also raised ethical concerns about biodesign practices, particularly regarding the domestication and use of living organisms under human control. While everyday activities like baking with yeast or consuming vegetables rarely face ethical scrutiny, designing with living organisms often elicits intuitive discomfort—this contrast creates an intriguing space for discussion. Though aimed at fostering sustainable futures and cultivating human sensitivity to more-than-human beings [9], it also sometimes confronts moral dilemmas surrounding the agency and treatment of the organisms involved.

Concerns about intervention and instrumentalization are not exclusive to public discourse—they frequently surface during the design process itself. For example, Wakkary et al. [58], in designing a sensory system for urban bees, considered minimizing disruptions to the bees' natural behaviors and relationships. Their question, "To what degree is human involvement warranted, beneficial, or avoidable?" underscores that intervention is not a binary issue but rather one of degree.

Speculative approaches, such as Chen et. al's *microbial revolt* [10], imagine lab tools and practices where living organisms resist human exploitation, encouraging designers to approach them with respect and awe. In a workshop hosted by Chen with a few biodesigners from our lab, including myself, we reflected upon ethical implications of our lab practices for the organisms we design with. This exercise resulted in a shocking ethical narrative about lab cyanobacteria:

In their wild habitats, they would be able to freely move around in various water bodies. They will encounter many different things and living creatures with which they interact. They will have predators and their life would be unpredictable. In my research artefacts, on the contrary, they were immobilized in hydrogel in order to better integrate into artefacts for everyday interaction. Their life seems more stable and "safe." Humans do actions to them, but they cannot respond back freely. They do not encounter any bugs, fish, algae, or potential predators. The only ones who can arbitrarily end their life—is their human co-habitants.

Even though with a certain level of romanticism, this exercise left me uneasy. In Chapter 4, I reflect on the implicit instrumentalization of cyanobacteria in designing the Cyano-chromic Interface and propose exploring less "human-intended" interfaces to reduce human dominance in biodesign practice. In future work, I will be guided more by an awareness of manual interventions during the design process. For instance, remaining liquid culture might be more critical where cyanobacteria have some degree of freedom to move around. Following Haraway's suggestion, I will be able to share pain, responsibility, and make conscious efforts to minimize harm to the living organism in mutual response-ability [53].

And this reflection makes me go back to the example of Living Root Bridges that I mentioned in the preface of the dissertation. In indigenous tribe of Khasi in Meghalaya, north-eastern India, people have mastered the art of making bridges from ficus trees that help them travel through dense tropical forests [59]. The Khasi villagers tie the aerial roots of the rubber tree (Ficus elastica) at both ends of the river to pieces of bamboo which help guide these roots towards each other and intertwine. In order to keep the trees healthy and their bridges long-lasting, Khasi people have adopted a sustainable lifestyle in deep connection and interdependancy with nature—areas within forests where extraction of natural resources is prohibited to allow natural regeneration, or a ban on hunting wildlife [59]. I find it a beautiful example of mutualistic relationships rooted in indigenous culture of human life.

Having reflected upon the ambivalance around instrumentalization and intervention, I would also like to point out a couple of dimensions to ethical ambivalences: one about situatedness, one about scale. The Khasi root bridges example reflect a normadic practice, a situated mutualistic care relation that is unique to the specific location, specific organism and specific people. Yet in ethical discussions, often, living organisms are associated strongly with the one and only "wildness," overlooking the specific, situated relationships that shape our entanglements. For instance, the cyanobacteria strain Synechocystis sp. PCC6803, used in my research, has been isolated and maintained in controlled lab conditions since 1968. While not "wild" in the conventional sense, these cyanobacteria invite us to consider how care can be enacted for such laboratory-bound organisms (Chapter 5). The challenge lies in navigating ethical narratives across situations and specificity, recognizing organisms as both situated beings whilst also part of broader ecological systems.

Moreover, scale is another dimension of ethical ambivalance I encountered. Biodesigners often form personal connections with the organisms they work with, treating them as companions rather than tools. For instance, a bioartist in my study hesitated to discard cyanobacteria cultures, believing in their potential to revive. Similarly, I asked a lab manager to care for my "cyanobacteria companions" during my absence. However, biodesigners must tread carefully when scaling their practices, as this could risk replicating industrialized approaches that reduce organisms to mere "workhorses." Balancing care, ethics, and practical design remains a central challenge for biodesign. Designers ought to recognize the multitude of ethics associated with designing with living organisms at different stages of development. These might include 1) living organisms as models and experimental fields in early lab exploration, 2) "workshorses" in and towards scaled up industrial production beyond designerly exploration, and 3) matters of care in new ecologies with human cohabitants that are situated in everyday life.

Ethical ambivalences are valuable in helping me generating alternative practices for future research. The first one I would like to explore is conceptualizing ecological assemblages as living materials. For example, designing with and caring for soil as an ecological assemblage of living entities [60]. This would bring the ecological relationships to the forefront and help to recognize the role of ecological entanglements in bringing functionality goal of biodesign. A recent work on multispecies interaction [61] provide biodesign frameworks that support designers to engage with not only single organisms but multiple, and their ecological relations. Another exploration I would like to delve into is rethinking contamination not as a failure but as a generative event of more-than-human ecologies. This might involve creating semi-open habitats [9] that invite emergences and embrace unintended interactions with multispecies. Examples like Flavo in Situ [15] demonstrate how semi-natural ecosystems can facilitate multispecies exchanges [61]. In this practice, though, balancing such openness with biosafety and care remains a challenge.

From Designing with to Designing-with the Living

To incorporate understanding of the world as more-than-human into biodesign practices might be filled with ambivalence as I have experienced, but we shall move forward with courage and care. As Donna Haraway nicely summarized in *When Species Meet*, "using a model organism in an experiment is a common necessity in research. The necessity and the justifications, no matter how strong, do not obviate the obligations of care and sharing pain." (p.70) And my dissertation encourages biodesigners to take a stance of care not only in their personal relationships with the organism, but also in the impact that their design makes in the world.

Besides, there is an urgent need for new ethical frameworks that better align with this perspective. Maria Puig de la Bellacasa aptly observes that, "we can observe a highly normative, also all-encompassing, 'risk management' approach to 'the ethics' of research in everyday legitimation strategies at work in organizations and institutions dedicated to producing knowledge. In the social sciences, a formalized regulation of research procedures often translates into a 'tick box' approach, in which ethics become programmatic and formulaic." [2](p.131) This critique highlights the limitations of current ethical frameworks, particularly when applied to the complex and evolving field of biodesign.

Encouragingly, researchers are beginning to speculate on what these new ethics might entail. For instance, Chen et al. [10] propose the concept of *microbial revolt* as a method to account for the non-participation of living organisms in biodesign lab and studio practices. This approach challenges traditional power dynamics and calls for a more inclusive consideration of microbial agency in biodesign process. Kim et al. propose a method of *becoming microbes*, as "immersing biodesigners in the realms of microbes with a fresh perspective for imagining the world through the lens of a microbe." [62] Similarly, [9] discuss the potential of living artefacts to contribute to "regenerative ecologies" — contexts characterized by mutualism, coevolution, and cohabitation. They outline five purposes for such artefacts, including the development of more-than-human sensibilities and ecological literacy, thereby linking the design of living artefacts to broader ecological and ethical goals. These emerging discourses illustrate the potential for biodesign to foster a more nuanced understanding of ethics, one that moves beyond narrow, utilitarian frameworks to consider the broader implications of our interactions with living organisms.

In search of a more encompassing way to advance this ethical shift, I align with the concept of "designing-with," as articulated by Ron Wakkary in his book *Things We Could Design for More-Than-Human-Centered Worlds* [38]. Wakkary advocates for a mentality of designing in collaboration with nonhuman entities, forming a design "constituency" that includes these participants as active stakeholders in the process. This approach calls for a reorientation of our role as designers—from those who initiate the design process to who consult with them and seriously consider their needs and contributions.

This shift in perspective should also extend beyond individual designers and researchers to include institutions. Imagine if research ethics committees were to scrutinize projects for their impact on microbial lives, ensuring that no harm comes to these living participants. Finally, I propose that design researchers open their bold design experiments for public discussion. This involves embracing unconventional methods, being unafraid of mistakes, and using those mistakes as learning opportunities for the community. This approach encourages transparency and invites others to engage with the process, contributing to a collective journey towards more-than-human care for the living things we design with. I hope that the three ambivalences I posed earlier can facilitate this process and inspire a more thoughtful and ethical approach to biodesign.

6.4. LIMITATIONS AND FUTURE WORK

In previous sections I have elaborated on implications of my work and suggested future research directions accordingly. In this section I will mention a few other limitations of my research and how future work can address them.

Firstly, there's an inherent tension in-between organism-specific approach that I am proposing in this dissertation, and generalization of the research to inform others. I have discussed earlier that the contributions of this disseration are transferable to broader biodesign and other design research fields. Yet, I am also aware that some specific studies on cyanobacterium *Synechocystis* sp. PCC6803, may not capture the unique temporalities and care needs of other cyanobacteria species, nor the broader realm of microbial lives. For example, shown in my first-person lived experiences, bioluminescent dinoflagellates showed a very different temporality, and thus a different temporal dissonance to design with. Even within the cyanobacteria themselves, there are differences across species, across individuals, which also evolve overtime within different environments. Here I would like to spend a few words to remind readers that the microbial world is a tapestry of rich diversity; thus, using "cyanobacteria" as a catch-all term in this dissertation simplifies for clarity and communication. Future research could delve into the delicate nuances of species-specific care relations, illuminating differences in findings.

Furthermore, this dissertation does not extend to other living organisms commonly explored in biodesign, such as fungi or plants, which operate on different spatial scales, temporal rhythms, and care needs. Nor does it encompass broader ecological systems beyond the confined spatial-temporal context of cohabiting with the living artefact. While this work advocates for the idea of multispecies flourishing, its focus remains on mutual thriving mediated by the photosynthetic outcomes of a single cyanobacterium. This should not be seen as an overreach, but rather as one situated interpretation—offered with an awareness of its limitations. In doing so, I acknowledges that, much like human care, the domain of multispecies care remains vast and largely uncharted, with many possibilities still waiting to unfold in future research.

Exploring materiality in isolation is just one facet of the broader landscape of design considerations. As indicated in Chapter 3, crafting the materiality of bio-digital artefacts holds the promise of unlocking a multitude of possibilities for interactions that could significantly enrich more-than-human relationships. Yet, it remains to be discovered how the materiality of digital artefacts can generate new possibilities in nurturing care. One foreseeable potential lies in synergizing digitally-controlled actuation with material qualities to create living artefacts that are both active and "powerful" in demanding care from people. For instance, wearable living artefacts that combine computational elements and pneumatic materials could generate bodily sensations, serving as a means of communication between humans and microbes, even nudging humans into certain care-related interactions[15]. Furthermore, as digital systems can detect and analyze microbial living status in a more comprehensive and nuanced manner, they can translate microbial needs into a variety of materials that exhibit diverse performativities, further enhancing the interplay between humans and their microbial cohabitants.

6.5. CONCLUSION

This dissertation responds to pressing issues of climate change, environmental crises, and the need for more ethical and sustainable relationships between humans and other living beings. Grounded in posthumanist, feminist care ethics and new materialist theories, it addresses the epistemological turn in design research toward fostering multispecies flourishing and challenging anthropocentric design paradigms. By focusing on the emerging field of biodesign, the research bridges a critical knowledge gap: how to design for reciprocal care relations between humans and living organisms, particularly microbes, through a lens of materiality.

Through a Research-through-Design methodology that integrates theoretical analysis, material-driven design, first-person experiences, imaginary artefacts, biological experiments, and longitudinal studies, this work examines three interrelated questions: crafting shared habitats for mutual well-being, addressing temporal dissonance in care, and fostering the creative unfolding of care practices in daily life. The dissertation's findings emphasize the potential of dynamic materiality to support living organisms' vitality, crafting habitabilities, bridge temporal dissonance, surface livingness, and elicit exploratory care practices.

It contributes to the fields of biodesign and more-than-human design research by offering theoretical, conceptual, empirical and methodological frameworks of more-than-human care. Particularly, it examplifies living artefacts that address human and microbial temporalities while fostering open-ended, situated, and creative practices of care, and offers empirical insights into the role of materiality in this process. It argues for a shift in biodesign toward embracing the relationality, unpredictability, temporality, performativity and complexity inherent in designing care towards living systems. In doing so, it opens up pathways for rethinking the social, ecological and ethical dimensions of biodesign and invites further exploration into how more-than-human care may "come to matter" through various ways, and how designers can facilitate multispecies flourishing within the messy, unpredictable realities of everyday life.

REFRENCES

[1] E. Karana, B. Barati, and E. Giaccardi. “Living Artefacts: Conceptualizing Livingness as a Material Quality in Everyday Artefacts.” In: *International Journal of Design* 14.3 (2020), pp. 37–53. URL: http://www.ijdesign.org/ index.php/IJDesign/article/view/3957/923.

[2] M. P. de la Bellacasa. *Matters of Care: Speculative Ethics in More than Human Worlds*. Minneapolis: University of Minnesota Press, 2017. ISBN: 9781517900656. URL: http://www.jstor.org/stable/10.5749/j. ctt1mmfspt (visited on 05/17/2023).

[3] D. Chen, Y. a. Seong, H. Ogura, Y. Mitani, N. Sekiya, and K. Moriya. “Nukabot: Design of Care for Human-Microbe Relationships”. 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: 10.1145/3411763.3451605. URL: https: //doi.org/10.1145/3411763.3451605.

[4] J. Lu and P. Lopes. “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/10.1145/3526113. 3545629.

[5] K. Helms and Y. Fernaeus. “Troubling Care: Four Orientations for Wickedness in Design”. In: *Proceedings of the 2021 ACM Designing Interactive Systems Conference*. DIS ’21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 789–801. ISBN: 9781450384766. DOI: 10.1145/3461778.3462025. URL: https://doi. org/10.1145/3461778.3462025.

[6] C. Key, F. Browne, N. Taylor, and J. Rogers. “Proceed with Care: Reimagining Home IoT Through a Care Perspective”. 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 .3445602. URL: https: //doi. org/10.1145/3411764.3445602.

[7] G. Oktay, Y. Ikeya, M. Lee, B. Barati, Y. Lee, Y. Chen, L. Pschetz, and C. Ramirez-Figueroa. “Designing with the More-than-Human: Temporalities of Thinking with Care”. In: *Companion Publication of the 2023 ACM Designing Interactive Systems Conference.* DIS ’23 Companion. Pittsburgh, PA, USA: Association for Computing Machinery, 2023, pp. 104–106. ISBN: 9781450398985. DOI: 10 .1145 /3563703 .3591462. URL: https: //doi. org/10.1145/3563703.3591462.

[8] R. Armstrong. “Biodesign for a culture of life: Of microbes, ethics, and design”. In: *Lockton, D., Lenzi, S., Hekkert, P., Oak, A., Sádaba, J., Lloyd, P. (eds.) Spain: DRS2022: Bilbao, 2022*, pp. 1–20. DOI: 10.21606/drs.2022.144. URL: https://doi.org/10.21606/drs.2022.144.

[9] E. Karana, H. McQuillan, V. Rognoli, and E. Giaccardi. “Living artefacts for regenerative ecologies”. In: *Research Directions: Biotechnology Design* 1 (2023), e16. DOI: 10.1017/ btd.2023.10.

[10] Y. Chen and L. Pschetz. “Microbial Revolt: Redefining biolab tools and practices for more-than-human care ecologies”. In: *Proceedings of the CHI Conference on Human Factors in Computing Systems*. CHI ’24. Association for Computing Machinery, 2024. ISBN: 9798400703300. DOI: 10.1145/3613904.3641981. URL: https://doi.org/10.1145/3613904.3641981.

[11] D. J. HARAWAY. “Making Kin: Anthropocene, Capitalocene, Plantationocene, Chthulucene”. In: *Staying with the Trouble: Making Kin in the Chthulucene*. Duke University Press, 2016, pp. 99–103. ISBN: 9780822362142. URL: http://www.jstor.org/stable/j.ctv11cw25q.9 (visited on 09/03/2024).

[12] K. Barad. “Posthumanist performativity: Toward an understanding of how matter comes to matter”. In: *Signs: Journal of women in culture and society* 28.3 (2003), pp. 801–831.

[13] K. Barad. *Meeting the universe halfway: Quantum physics and the entanglement of matter and meaning*. Duke University Press (2007).

[14] K. Höök and J. Löwgren. “Strong concepts: Intermediate-level knowledge in interaction design research”. In: *ACM Trans. Comput.-Hum. Interact*. 19.3 (Oct. 2012). ISSN: 1073-0516. DOI: 10.1145/2362364.2362371. URL: https://doi.org/10.1145/2362364.2362371.

[15] R. Kim, C. Risseeuw, E. G. Groutars, and E. Karana. “Surfacing Livingness in Microbial Displays: A Design Taxonomy for HCI”. 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 .3581417. URL: https: //doi.org/10.1145/3544548.3581417.

[16] J. Zhou, R. Kim, Z. Doubrovski, J. Martins, E. Giaccardi, and E. Karana. “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/10.1145/3563657.3596132.

[17] W. Odom, R. Banks, A. Durrant, D. Kirk, and J. Pierce. “Slow Technology: Critical Reflection and Future Directions”. In: *Proceedings of the Designing Interactive Systems Conference.* DIS ’12. Newcastle Upon Tyne, United Kingdom: Association for Computing Machinery, 2012, pp. 816–817. ISBN: 9781450312103. DOI: 10 .1145 /2317956 .2318088. URL: https: //doi.org/10.1145/2317956.2318088.

[18] W. T. Odom, A. J. Sellen, R. Banks, D. S. Kirk, T. Regan, M. Selby, J. L. Forlizzi, and J. Zimmerman. “Designing for Slowness, Anticipation and Re-Visitation: A Long Term Field Study of the Photobox”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’14. Toronto, Ontario, Canada: Association for Computing Machinery, 2014, pp. 1961–1970. ISBN: 9781450324731. DOI: 10.1145/2556288.2557178. URL: https://doi.org/10.1145/2556288.2557178.

[19] W. Odom, R. Wakkary, I. Bertran, M. Harkness, G. Hertz, J. Hol, H. Lin, B. Naus, P.

Tan, and P. Verburg. “Attending to Slowness and Temporality with Olly and Slow Game: A Design Inquiry Into Supporting Longer-Term Relations with Everyday Computational Objects”. 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: 10.1145/3173574.3173651. URL: https://doi.org/10.1145/3173574.3173651.

[20] L. Pschetz and M. Bastian. “Temporal Design: Rethinking time in design”. In: *Design Studies* 56 (2018), pp. 169–184.

[21] L. Pschetz, K. Koppel, and M. Bastian. “Design for Temporal Cohabitation”. In: *Extended Abstracts of the 2024 CHI Conference on Human Factors in Computing Systems.* CHI EA ’24. Association for Computing Machinery, 2024. ISBN: 9798400703317. DOI: 10.1145/3613905.3644068. URL: https: //doi.org/10.1145/3613905.3644068.

[22] T. Merritt, F. Hamidi, M. Alistar, and M. DeMenezes. “Living media interfaces: a multi-perspective analysis of biological materials for interaction”. In: *Digital Creativity* 31.1 (2020), pp. 1–21. ISSN: 17443806. DOI: 10.1080/14626268. 2019.1707231.

[23] E. G. Groutars, C. C. Risseeuw, C. Ingham, R. Hamidjaja, W. S. Elkhuizen, S. C. Pont, and E. Karana. “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.* CHI ’22. New Orleans, LA, USA: Association for Computing Machinery, 2022. ISBN: 9781450391573. DOI: 10.1145/3491102.3517713. URL: https: //doi.org/10.1145/3491102.3517713.

[24] I. Henriques. Caravel - environmental robot. 2016. URL: https:// www.zdnet.com/article/microbial-marketing-bacteria-and-fungi- infect-contagions-billboard/.

[25] E. N. for Environmental Citizenship – ENEC. Defining Education for Environmental Citizenship. 2018. URL: https://enec- cost.eu /our- approach/education-for-environmental-citizenship/.

[26] J. C. Tronto. *Moral Boundaries: A Political Argument for an Ethic of Care.* New York, NY: Routledge, 1993.

[27] P. van Allen, J. McVeigh-Schultz, B. Brown, H. M. Kim, and D. Lara. “AniThings: Animism and Heterogeneous Multiplicity”. In: *CHI ’13 Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’13. Paris, France: Association for Computing Machinery, 2013, pp. 2247–2256. ISBN: 9781450319522. DOI: 10 .1145 /2468356 .2468746. URL: https: //doi.org/10.1145/2468356.2468746.

[28] E. Giaccardi and E. Karana. “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.

[29] W. W. Gaver, J. Beaver, and S. Benford. “Ambiguity as a resource for design”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’03. Ft.

Lauderdale, Florida, USA: Association for Computing Machinery, 2003, pp. 233–240. ISBN: 1581136307. DOI: 10.1145/642611.642653. URL: https://doi.org/10.1145/642611.642653.

[30] W. W. Gaver, J. Bowers, A. Boucher, H. Gellerson, S. Pennington, A. Schmidt, A. Steed, N. Villars, and B. Walker. “The drift table: designing for ludic engagement”. In: *CHI '04 Extended Abstracts on Human Factors in Computing Systems (CHI EA '04).* New York, NY, USA: Association for Computing Machinery, 2004, ppp. 885-900. URL: https://doi.org/10.1145/985921.985947

[31] C. Zhong, R. Wakkary, A. Y. S. Chen, and D. Oogjes. “deformTable: Crafting a Shape-changing Device for Creative Appropriations Over Time”. In: *Proceedings of the 2021 ACM Designing Interactive Systems Conference.* DIS ’21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 1253–1265. ISBN: 9781450384766. DOI: 10.1145/3461778.3462112. URL: https://doi.org/10.1145/3461778.3462112.

[32] R. Wakkary, D. Oogjes, H. W. J. Lin, and S. Hauser. “Philosophers Living with the Tilting Bowl”. 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/ 3173574.3173668. URL: https://doi.org/10.1145/3173574.3173668.

[33] L. Kuijer, I. Nicenboim, and E. Giaccardi. “Conceptualising Resourcefulness as a Dispersed Practice”. In: *Proceedings of the 2017 Conference on Designing Interactive Systems*. DIS ’17. Edinburgh, United Kingdom: Association for Computing Machinery, 2017, pp. 15–27. ISBN: 9781450349222. DOI: 10.1145/ 3064663.3064698. URL: https://doi.org/10.1145/3064663.3064698.

[34] E. Giaccardi and I. Nicenboim. Resourceful Ageing: Empowering Older People to Age Resourcefully with the Internet of Things. Original work published 2018. Delft, NL: TU Delft OPEN Publishing, 2023. DOI: 10.59490/mg.76. URL: https://doi.org/10.59490/mg.76.

[35] S. B. Evert van Beek Elisa Giaccardi and A. Bozzon. “The everyday enactment of interfaces: a study of crises and conflicts in the more-than-human home”. In: *Human–Computer Interaction* 0.0 (2023), pp. 1–28. DOI: 10.1080/07370024. 2023.2283536. URL: https://doi.org/10.1080/07370024.2023.2283536.

[36] E. Karana, B. Barati, V. Rognoli, A. Zeeuw Van Der Laan, et al. “Material driven design (MDD): A method to design for material experiences”. In: *International Journal of Design* 9.2 (2015), pp. 35–54.

[37] F. Bell, J. Coffie, and M. Alistar. “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/10.1145/3623509.3633386.

[38] R. Wakkary. *Things we could design: For more than human-centered worlds*. Cambridge, MA: MIT press, 2021.

[39] H. B. Iohanna Nicenboim Doenja Oogjes and S. Nam. “Decentering Through De-

sign: Bridging Posthuman Theory with More-than-Human Design Practices". In: *Human–Computer Interaction* 0.0 (2023), pp. 1–26. DOI: 10.1080/07370024.2023.2283535. eprint: https://doi.org/10.1080/07370024.2023.2283535. URL: https://doi.org/10.1080/07370024.

2023.2283535.

[40] J. R. Elisa Giaccardi and I. Nicenboim. "The making(s) of more-than-human design: introduction to the special issue on more-than-human design and HCI". In: *Human–Computer Interaction* 0.0 (2024), pp. 1–16. DOI: 10.1080/ 07370024.2024.2353357. eprint: https://doi.org/10.1080/07370024.2024.2353357. URL: https://doi.org/10.1080/07370024.2024.2353357.

[41] B. Pollini. "From biodesigners to designers in lab: testing the nuances of an emerging profession through autoethnography". In: *Research Directions: Biotechnology Design* 2 (2024), e20. DOI: 10.1017/btd.2024.11.

[42] B. Latour. "Why has Critique Run Out of Steam? From Matters of Fact to Matters of Concern". In: *Critical Inquiry* 30.2 (2004), pp. 225–248. DOI: 10.1086/421123.

[43] R. Wakkary. "A participatory design understanding of interaction design". In: *environment* 5 (2007), p. 18.

[44] D. Wilde and T. Lenskjold. "Shit! Towards an experimental multiple-perspective approach to human-microbiome relations". In: *Human–Computer Interaction* 0.0 (2023), pp. 1–28. DOI: 10.1080/07370024.2023.2276527. URL: https://doi.org/10.1080/07370024.2023.2276527.

[45] R. Clarke, S. Heitlinger, A. Light, L. Forlano, M. Foth, and C. DiSalvo. "More-than-human participation: design for sustainable smart city futures". In: *interactions* 26.3 (2019), pp. 60–63.

[46] Y. Akama, A. Light, and T. Kamihira. "Expanding Participation to Design with More-Than-Human Concerns". In: *Proceedings of the 16th Participatory Design Conference 2020 - Participation(s) Otherwise* - Volume 1. PDC '20. Manizales, Colombia: Association for Computing Machinery, 2020, pp. 1–11. ISBN: 9781450377003. DOI: 10.1145/3385010.3385016. URL: https://doi.org/10.1145/3385010.3385016.

[47] A. Light. "More-than-Human Participatory Approaches for Design: Method and Function in Making Relations". In: *Proceedings of the Participatory Design Conference 2024: Exploratory Papers and Workshops* - Volume 2. PDC '24. Sibu, Malaysia: Association for Computing Machinery, 2024, pp. 1–6. ISBN: 9798400706547. DOI: 10.1145/3661455.3669862. URL: https://doi.org/10.1145/3661455.3669862.

[48] A. H. Eagly. "The psychology of attitudes". In: *Thomson Wadsworth* (1993).

[49] R. Kim, J. Zhou, E. G. Groutars, and E. Karana. "Designing living artefacts: Opportunities and challenges for biodesign". In: *DRS2022: Bilbao. DRS2022. Design Research Society*, June 2022. DOI: 10.21606/drs.2022.942. URL: http://dx.doi.org/10.21606/drs.2022.942.

[50] J. M. Gonzalez and B. Aranda. "Microbial Growth under Limiting Conditions- Future Perspectives". In: *Microorganisms* 11.7 (2023). ISSN: 2076-2607. DOI: 10.3390/microor-

ganisms11071641. URL: https://www.mdpi.com/2076- 2607/11/7/1641.

[51] L. A. Zinke, M. M. Mullis, J. T. Bird, I. P. G. Marshall, B. B. Jørgensen, K. G. Lloyd, J. P. Amend, and B. Kiel Reese. “Thriving or surviving? Evaluating active microbial guilds in Baltic Sea sediment”. In: *Environmental Microbiology Reports* 9.5 (2017), pp. 528–536. DOI: https://doi.org/ 10.1111/1758- 2229.12578. eprint: https://enviromicro-journals. onlinelibrary.wiley.com/doi/pdf/10.1111/1758-2229.12578. URL: https://enviromicro-journals.onlinelibrary.wiley.com/doi/abs/ 10.1111/1758-2229.12578.

[52] N. Kumar, S. Chaturvedi, and S. P. Khurana. “Survival and thriving behavior of bacteria in microbial jungle”. In: *Microbial Resource Technologies for Sustainable Development*. Elsevier, 2022, pp. 1–21.

[53] D. J. Haraway. *When Species Meet*. Vol. 3. University of Minnesota Press, 2008.

[54] B. Franks, C. Webb, M. Gagliano, and B. Smuts. “Conventional science will not do justice to nonhuman interests: A fresh approach is required”. In: *Animal Sentience* 4.27 (2020), p. 17.

[55] A. Murphy. “Imagination in science”. In: *Philosophy Compass* 17.6 (2022), e12836.

[56] M. Frappier, L. Meynell, and J. R. Brown. *Thought experiments in science, philosophy, and the arts*. Routledge, 2012.

[57] M. Ivanova and S. French. *Aesthetics of Science: Beauty, Imagination and Understanding Introduction to the Volume*. Routledge, 2020.

[58] R. Wakkary, D. Oogjes, N. Sakib, and A. Behzad. “Turner Boxes and Bees: From Ambivalence to Diffraction”. In: *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. DIS ’23. Pittsburgh, PA, USA: Association for Computing Machinery, 2023, pp. 790–807. ISBN: 9781450398930. DOI: 10.1145/3563657.3596081. URL: https://doi. org/10.1145/3563657.3596081.

[59] United Nations Development Programme. Conserving the living root bridges of Meghalaya. May 2024. URL: https://www.undp.org/stories/conserving-living-root-bridges-meghalaya/.

[60] M. P. de la Bellacasa. “Re-animating soils: Transforming human–soil affections through science, culture and community”. In: *The Sociological Review* 67.2 (2019), pp. 391–407. DOI: 10.1177/0038026119830601. eprint: https://doi.org/10.1177/0038026119830601. URL: https: //doi.org/10.1177/0038026119830601.

[61] E. G. Groutars, R. Kim, and E. Karana. “Designing living artefacts for multispecies interactions: An ecological approach”. In: *International Journal of Design* 18.2 (2024), pp. 59–78.

[62] J. Kim, R. Kim, J. Martins, and E. Karana. “Becoming microbes: An approach to cultivating microbial sensibilities in biodesign”. In: *Proceedings of DRS. Design Research Society*, June 2024.

Summary

Today, the challenges of climate change and environmental crises are widely acknowledged as urgent global concerns. Against this backdrop, and informed by the epistemological turns of posthumanism, design research seeks to challenge and expand conventional paradigms. For the shared goal of "living as well as possible" with other earthly beings, it is essential to understand the intricate and dynamic relations we share with the (living) entities we design and cohabit with. Grounded in posthumanist, feminist care, and new materialist theories, this dissertation investigates **care** in biodesign, focusing on cultivating care relations between humans and living organisms, particularly **microbes**. Through exploring materiality as a lens for designing more-than-human care, it offers theoretical, conceptual, empirical, and methodological contributions to the expanding discourse on care in designing with living systems.

This dissertation employs a programmatic Research-through-Design process. A multiplicity of methods such as theoretical analysis, auto-ethnography, imaginary artefacts, material-driven design and a longitudinal ethnographic study are deployed. Within the research program, I conducted two main design experiments, including the creation of cyanobacteria-based living artefacts and the characterization of their temporal patterns.

The main objective of this dissertation is to explore how more-than-human care can be facilitated within and through biodesign practices. Complementing this, the dissertation also intends to explore ways of understanding and engaging with a specific other-than-human living entity thoroughly—a microbe—whilst acknowledging the limitation of the human perspective. To ground the exploration, the dissertation focuses on the care for cyanobacteria, a group of photosynthetic microorganisms with potential for carbon fixation and oxygen release. These objectives are addressed through three interrelated and accumulative research questions.

1) How can we craft the shared habitats of human and living artefacts for their mutual well-being?

2) How can we design with temporal dissonance to foster reciprocal relationships between humans and living artefacts?

3) How can we foster the creative unfolding of care practices for living

artefacts in everyday life?

Below, I outline the research activities done and key findings to address each question.

1) How can we craft the shared habitats of human and living artefacts for their mutual well-being?

The first question establishes an overarching aim of fostering multispecies relationality and flourishing in biodesign. To address it, I began with a comprehensive review of literature and practice on designing with living organisms, highlighting my positional stance of viewing humans and living artefacts as inherently relational in biodesign. From this foundation, I propose the biodesign continuum—a framework that positions designing living artefacts as an iterative process of configuring and reconfiguring shared habitats through the ongoing practices of understanding, embodying, and perpetuating those habitats. Along this continuum, I present a taxonomy of digital tools for crafting habitabilities of living artefacts, offering a practical resource for biodesigners to situate and develop novel tools for mutual thriving.

This exploration also uncovers an opportunity for leveraging dynamic materials, complementing the more widely applied digital technologies in biodesign. Through these studies, I refine my focus on crafting care relations within shared habitats and identify a critical gap: the role of direct material engagement in fostering these relations. Furthermore, I address the unique challenges of designing care relations with microbes, particularly due to their microscopic scale and distinct temporalities.

This process sharpened my research focus on crafting care relations with microbes through materiality. To delve deeper into this space, I engaged in my first-person lived experiences with two microbes—the bioluminescent dinoflagellate *Pyrocystis lunula* and the cyanobacterium *Spirulina platensis*—over several months. During this time, I took care of them, observed their temporal changes, and experimented to develop a deeper understanding of our care relations. Through this process, I identified the critical need for timely understanding of the microbes' living states to cultivate care effectively, highlighting the challenge of noticing microbial temporalities that hinder such understanding. Additionally, I uncovered a tension between the prescriptive nature of care instructions and the unpredictable, dynamic realities of living systems and everyday life. I synergized these reflections by envisioning how materiality could address these challenges, speculating on living artefacts that foster human-microbe care relations.

While these speculations pointed to promising directions, they also revealed potential technical challenges in realizing such ideas. These initial explorations significantly shaped the subsequent research questions 2 and 3, which are unpacked in the following chapters. To address these challenges, I conducted further design experiments, detailed in Chapters 4 and 5.

2) How can we design with temporal dissonance to foster reciprocal relationships between humans and living artefacts?

Building on insights from the first research question, this inquiry introduces the concept of *temporal dissonance*—the time lag humans experience in noticing the metabolic changes of certain microbes in the context of living artefacts in biodesign. While this dissonance can hinder timely care, designing with it can also offer a generative opportunity to foster reciprocal relationships between humans and microbes. To explore this potential, I focus on how dynamic materials can be leveraged to help humans notice microbes and their temporalities within and through living artefacts, and examine the design space this creates.

Two living artefacts were introduced to exemplify this approach. The first, *Cyanochromic Interface* (Chapter 4), uses an electrochromic (EC) material to surface the photosynthetic activity of the cyanobacterium *Synechocystis* sp. PCC6803, providing a monochromatic visual indicator of its living state. I characterized the interface effect, developed design primitives, and proposed application concepts as imaginary artefacts that demonstrate its adaptability across various contexts to foster reciprocal relationships with microbes.

The second artefact, the *Living Cyanobacteria Artefact* (Chapter 5), integrates a pH- indicating substance that visually displays cyanobacteria's photosynthetic activity through color changes occurring over several hours. A longitudinal study with this artefact revealed how such dynamic materials interface enhance care knowledge by making microbial living states more perceptible, thus elicit affection and appreciation of microbes and elicit care actions.

3) How can we foster the creative unfolding of care practices for living artefacts in everyday life?

The third question further addresses the gap and challenge identified in the first question. It investigates how materiality and dynamic, non-prescriptive care approaches can support the unpredictable and evolving relationships humans have with living artefacts in everyday contexts. This inquiry is explored in Chapter 5. Building on the premise that the materiality of artefacts significantly influences daily practices, particularly through their performative qualities, I designed the *Living Cyanobacteria Artefact*. This artefact integrates air-purifying functionality with dynamic material properties like color-changing, pliability, adhesiveness, and suspendability, allowing individuals to place it in various locations based on air purification needs and optimal lighting for its vitality. Eight participants with varying experiences in caretaking for other-than-human entities lived with the artefact for two weeks.

The longitudinal study revealed key roles of materiality in nurturing care practices in creative ways:

1) *Increasing Habitat Resilience to Support Care Labour*: Materiality can support the artefact's viability and can flexibly adjust care labour by making the artefact resilient to various environmental conditions and care requirements.

2) *Surfacing Livingness to Enhance Care Knowledge*: Temporal qualities of materials, such as colour-change triggered by the living state changes of cyanobacteria, deepens knowledge of the artefact's liivng states and temporalities, and shapes affection and appreciation.

3) *Tuning Performativity to Elicit Exploratory Care*: The artefact's performative material qualities invite exploratory and intuitive placement and attachment, encouraging individuals to creatively navigate both the functional role and the thriving of the living artefact.

The study also identified a few design dimensions that designers should thoughtfully considerate when navigating the roles of materiality. These dimensions include: 1) temporal dissonance and alignment, 2) familiar and unfamiliar living aesthetics, and 3) prescriptive and exploratory care. By reaching a delicate balance in each dimension, designers can ensure that materiality meets the specific care needs of living organisms, while also addressing the broader demands of the design context, such as cultivating more-than-human sensibilities.

I offer several contributions to biodesign and more-than-human design research, categorized under theoretical and conceptual, empirical, and methodological and practical themes. Theoretical and conceptual contributions include the proposal of mattering more-than-human care in biodesign, a biodesign continuum framework for crafting habitatbilities, and the concept of temporal dissonance in designing for human-microbe reciprocity. Empirical insights encompass the role of material qualities in fostering more-than-human care, insights on mutualistic care, and technical and experiential knowledge on designing with cyanobacteria. Methodological and practical contributions include a taxonomy of digital tools for crafting habitabilities, methods for designing temporal-aligning living artefacts, a method for designing microbial living artefacts for longitudinal studies, and a method for creating performative and multi-situated microbial living artefacts.

In the concluding chapter (Chapter 6), I summarize my contributions, reflect on methodology and ambivalances encountered in the research process. I discuss the contributions to the fields of biodesign and more-than-human design research, especially how they connect back to theories. I then reflect on my Research-through-Design process, theory-practice positioning and designerly ways of knowing. I also reflect on the practical, epistemological and ethical ambivalences I have encountered in my research, which is at the intersection of biodesign and more-than-human design. Finally I outline a couple of limitations of the research.

The dissertation concludes by advocating for embracing relationality, ongoingness, diverse temporalities, and material entanglements inherent in more-than-human care in biodesign. This dissertation opens pathways for rethinking the social, ecological, and ethical dimensions of biodesign while offering conceptual, methodological and empirical tools and insights for designers to explore care in more-than-human contexts. It calls for a practice deeply attentive to the nuances of materiality, recognizing its potential to shape care relations in creative and situated ways, and encouraging a thoughtful engagement with the diverse temporalities, dynamics, and interdependencies of multispecies flourishing.

Sammenvatting

Vandaag worden de uitdagingen van klimaatverandering en milieucrisissen algemeen erkend als urgente mondiale kwesties. Tegen deze achtergrond, en geïnformeerd door de epistemologische wendingen van het posthumanisme, probeert ontwerponderzoek conventionele paradigma's uit te dagen en uit te breiden. Voor het gedeelde doel van "zo goed mogelijk samenleven"met andere aardse wezens, is het essentieel om de complexe en dynamische relaties die we delen met de (levende) entiteiten waarmee we ontwerpen en samenleven te begrijpen. Gebaseerd op posthumanistische, feministische zorg en nieuw-materialistische theorieën onderzoekt dit proefschrift **zorg** in biodesign, met een focus op het cultiveren van zorgrelaties tussen mensen en levende organismen, in het bijzonder **microben**. Door materialiteit te verkennen als een lens voor het ontwerpen van meer-dan-menselijke zorg, biedt het theoretische, conceptuele, empirische en methodologische bijdragen aan het groeiende discours over zorg in ontwerpen met levende systemen.

Dit proefschrift maakt gebruik van een programmatisch Research-through-Design proces. Een veelvoud aan methoden, zoals theoretische analyse, auto-etnografie, imaginaire artefacten, materiaalgestuurd ontwerpen en een longitudinale etnografische studie, worden toegepast. Binnen het onderzoeksprogramma heb ik twee hoofdontwerpexperimenten uitgevoerd, waaronder het creëren van op cyanobacteriën gebaseerde levende artefacten en het karakteriseren van hun temporele patronen.

Het hoofddoel van dit proefschrift is om te onderzoeken hoe meer-dan-menselijke zorg kan worden gefaciliteerd binnen en door biodesignpraktijken. Als aanvulling hierop beoogt het proefschrift ook manieren te verkennen om een specifieke niet-menselijke levende entiteit—een microbe—grondig te begrijpen en ermee om te gaan, terwijl de beperkingen van het menselijke perspectief worden erkend. Om de verkenning te funderen richt het proefschrift zich op de zorg voor cyanobacteriën, een groep fotosynthetische microorganismen met potentieel voor koolstoffixatie en zuurstofproductie. Deze doelstellingen worden aangepakt door middel van drie onderling verbonden en accumulatieve onderzoeksvragen.

1) Hoe kunnen we de gedeelde habitats van mensen en levende artefacten vormgeven voor wederzijdse bloei?

2) Hoe kunnen we ontwerpen met temporele dissonantie om wederkerige

relaties tussen mensen en levende artefacten te bevorderen?

3) Hoe kunnen we de creatieve ontplooiing van zorgpraktijken voor levende artefacten in het dagelijks leven stimuleren?

Hieronder geef ik een overzicht van de uitgevoerde onderzoeksactiviteiten en de belangrijkste bevindingen voor elke vraag.

1) Hoe kunnen we de gedeelde habitats van mensen en levende artefacten vormgeven voor wederzijdse bloei?

De eerste vraag stelt een overkoepelend doel vast: het bevorderen van multispecies-relationaliteit en bloei in biodesign. Om deze vraag te beantwoorden, begon ik met een uitgebreide literatuuren praktijkreview over ontwerpen met levende organismen, waarin ik mijn standpunt benadrukte dat mensen en levende artefacten inherent relationeel zijn in biodesign. Vanuit deze basis stel ik het biodesigncontinuüm voor—een kader dat het ontwerpen van levende artefacten positioneert als een iteratief proces van het configureren en herconfigureren van gedeelde habitats via voortdurende praktijken van begrijpen, belichamen en in stand houden van die habitats. Langs dit continuüm presenteer ik een taxonomie van digitale tools voor het vormgeven van leefomgevingen van levende artefacten, als een praktische bron voor biodesigners om nieuwe tools te situeren en te ontwikkelen voor wederzijdse bloei.

Deze verkenning onthult ook een kans om dynamische materialen te benutten als aanvulling op de meer wijdverbreide digitale technologieën in biodesign. Door deze studies richt ik me verder op het vormgeven van zorgrelaties binnen gedeelde habitats en identificeer ik een kritische lacune: de rol van directe materiaalinteractie in het bevorderen van deze relaties. Bovendien behandel ik de unieke uitdagingen van ontwerpen van zorgrelaties met microben, met name vanwege hun microscopische schaal en specifieke temporaliteiten.

Dit proces verscherpte mijn onderzoeksfocus op het vormgeven van zorgrelaties met microben door middel van materialiteit. Om dieper in dit gebied te duiken, ging ik in op mijn eigen ervaringen met twee microben—de bioluminescente dinoflagellaat Pyrocystis lunula en de cyanobacterie Spirulina platensis—over meerdere maanden. Gedurende deze tijd zorgde ik voor hen, observeerde ik hun temporele veranderingen en experimenteerde ik om een diepere begrip van onze zorgrelaties te ontwikkelen. Door dit proces identificeerde ik de kritische noodzaak van tijdig begrip van de leefstaten van microben om zorg effectief te cultiveren, en benadrukte ik de uitdaging om microbiale temporaliteiten waar te nemen die dergelijk begrip belemmeren. Daarnaast ontdekte ik een spanning tussen de voorschrijvende aard van zorginstructies en de onvoorspelbare, dynamische realiteiten van levende systemen en het dagelijks leven. Ik verenigde deze reflecties door te speculeren hoe materialiteit deze uitdagingen zou kunnen aanpakken, en speculeerde op levende artefacten die menselijke-microbiale zorgrelaties bevorderen.

Hoewel deze speculaties veelbelovende richtingen suggereerden, onthulden ze ook potentiële technische uitdagingen om dergelijke ideeën te realiseren. Deze initiële verkenningen vormden de basis voor de daaropvolgende onderzoeksvragen 2 en 3, die in de volgende hoofdstukken worden uitgepakt. Om deze uitdagingen aan te pakken voerde ik verdere ontwerpexperimenten uit, gedetailleerd in Hoofdstukken 4 en 5.

2) Hoe kunnen we ontwerpen met temporele dissonantie om wederkerige relaties tussen mensen en levende artefacten te bevorderen?

Voortbouwend op de inzichten uit de eerste onderzoeksvraag introduceert dit onder zoek het concept van temporele dissonantie—de vertraging die mensen ervaren bij het opmerken van de metabolische veranderingen van bepaalde microben in de context van levende artefacten in biodesign. Hoewel deze dissonantie tijdige zorg kan belemmeren, kan ontwerpen met deze dissonantie ook een generatieve kans bieden om wederkerige relaties tussen mensen en microben te bevorderen. Omdit potentieel te verkennen, richt ik me op hoe dynamische materialen kunnen worden benut om mensen te helpen microben en hun temporaliteiten in en via levende artefacten op te merken, en onderzoek ik de ontwerpruimte die hierdoor ontstaat.

Twee levende artefacten werden geïntroduceerd om deze benadering te illustreren. Het eerste, *Cyano-chromic Interface* (Hoofdstuk 4), gebruikt een elektrochromisch (EC) materiaal om de fotosynthetische activiteit van de cyanobacterie *Synechocystis* sp. PCC6803 zichtbaar te maken, wat een monochrome visuele indicator biedt van de levende staat ervan. Ik karakteriseerde het interface-effect, ontwikkelde ontwerpprimitieven en stelde "toepassingsconcepten"voor als imaginaire artefacten die de aanpasbaarheid ervan in verschillende contexten aantonen om wederkerige relaties met microben te bevorderen.

Het tweede artefact, het *Living Cyanobacteria Artefact* (Hoofdstuk 5), integreert een pH-indicerende substantie die de fotosynthetische activiteit van cyanobacteriën visueel weergeeft door kleurveranderingen over meerdere uren. Een longitudinaal onderzoek met dit artefact onthulde hoe dergelijke dynamische materialen de zorgkennis verbeteren door de leefstaten van microben beter waarneembaar te maken, wat affectie en waardering voor microben en zorgacties oproept.

3) Hoe kunnen we de creatieve ontplooiing van zorgpraktijken voor levende artefacten in het dagelijks leven stimuleren?

De derde vraag gaat verder in op de lacune en uitdaging geïdentificeerd in de eerste vraag. Het onderzoekt hoe materialiteit en dynamische, niet-voorschrijvende zorgbenaderingen de onvoorspelbare en evoluerende relaties die mensen hebben met levende artefacten in alledaagse contexten kunnen ondersteunen. Deze vraag wordt onderzocht in Hoofdstuk 5.

Gebaseerd op de premisse dat de materialiteit van artefacten dagelijkse praktijken significant beïnvloedt, vooral door hun performatieve kwaliteiten, ontwierp ik het *Living Cyanobacteria Artefact*. Dit artefact integreert een luchtzuiverende functionaliteit met dynamische materiaaleigenschappen zoals kleurverandering, buigzaamheid, kleefkracht en ophangbaarheid, waardoor individuen het in diverse locaties kunnen plaatsen afhankelijk van de behoefte aan luchtzuivering en optimale verlichting voor de vitaliteit van het artefact. Acht deelnemers met uiteenlopende ervaringen in de zorg voor niet-menselijke entiteiten leefden gedurende twee weken met het artefact.

De longitudinale studie bracht enkele sleutelrollen van materialiteit aan het licht in het stimuleren van zorgpraktijken op creatieve manieren:

Vergroten van habitatresiliëntie ter ondersteuning van zorghandelingen: Materialiteit kan de levensvatbaarheid van het artefact ondersteunen en flexibel de zorghandelingen aanpassen door het artefact veerkrachtig te maken tegen uiteenlopende omgevingsomstandigheden en zorgvereisten.

Zichtbaar maken van levendigheid om zorgkennis te vergroten: Temporele kwaliteiten van materialen, zoals kleurverandering die wordt getriggerd door veranderingen in de leefstaten van cyanobacteriën, verdiepen de kennis van de levende staat en temporaliteiten van het artefact, wat affectie en waardering stimuleert.

Afstemmen van performativiteit om exploratieve zorg te stimuleren: De performatieve materiaaleigenschappen van het artefact nodigen uit tot exploratieve en intuïtieve plaatsing en bevestiging, wat individuen aanmoedigt om zowel de functionele rol als de bloei van het levende artefact op creatieve manieren te navigeren.

De studie identificeerde ook enkele ontwerpdimensies die ontwerpers zorgvuldig moeten overwegen bij het balanceren van de rollen van materialiteit. Deze dimensies omvatten: 1) temporele dissonantie en afstemming, 2) vertrouwde en niet-vertrouwde levende esthetiek, en 3) voorschrijvende en exploratieve zorg.

Door een delicate balans te vinden in elke dimensie, kunnen ontwerpers ervoor zorgen dat materialiteit voldoet aan de specifieke zorgbehoeften van levende organismen, terwijl ook tegemoet wordt gekomen aan bredere ontwerpeisen, zoals het cultiveren van meer-dan-menselijke sensibiliteiten.

Ik bied verschillende bijdragen aan biodesign en meer-dan-menselijke ontwerppraktijken, gecategoriseerd onder theoretische en conceptuele, empirische, en methodologische en praktische thema's. Theoretische en conceptuele bijdragen: het voorstellen van zorg in biodesign vanuit een meer-dan-menselijk perspectief, een biodesign continuüm voor het vormgeven van habitabiliteiten, en het concept van temporele dissonantie bij ontwerpen voor menselijke-microbiale wederkerigheid. Empirische inzichten: de rol van materiaaleigenschappen in het bevorderen van meer-dan-menselijke zorg, inzichten in mutualistische zorg, en technische en ervaringskennis bij het ontwerpen met cyanobacteriën. Methodologische en praktische bijdragen: een taxonomie van digitale tools voor het vormgeven van habitabiliteiten, methoden voor het ontwerpen van temporeel-afstemmende levende artefacten, een methode voor het ontwerpen van microbiale levende artefacten voor longitudinale studies, en een methode voor het creëren van performatieve en multi-situated microbiale levende artefacten.

In het slothoofdstuk (Hoofdstuk 6) vat ik mijn bijdragen samen en reflecteer ik op de methodologie en ambivalenties die tijdens het onderzoeksproces zijn ervaren. Ik bespreek de bijdragen aan de velden van biodesign en meer-dan-menselijke ontwerppraktijken, met name hoe deze terugkoppelen naar theorieën. Verder reflecteer ik op mijn Research-through-Design proces, theorie-praktijkpositionering en ontwerpgerichte manieren van kennisvorming. Daarnaast ga ik in op de praktische, epistemologische en ethische ambivalenties die ik tegenkwam in mijn onderzoek op het snijvlak van biodesign en meer-dan-menselijk ontwerp. Tot slot schets ik enkele beperkingen van het onderzoek.

De dissertatie besluit met een pleidooi voor het omarmen van relationaliteit, voortdurende processen, diverse temporaliteiten en materiële verwevenheden die inherent zijn aan meer-dan-menselijke zorg in biodesign. Deze dissertatie opent wegen om sociale, ecologische en ethische dimensies van biodesign te heroverwegen en biedt conceptuele, methodologische en empirische tools en inzichten voor ontwerpers om zorg in meer-dan-menselijke contexten te verkennen. Het roept op tot een praktijk die aandachtig is voor de nuances van materialiteit, die haar potentieel erkent om zorgrelaties op creatieve en gesitueerde manieren vorm te geven, en die een zorgvuldige betrokkenheid bevordert bij de diverse temporaliteiten, dynamieken en interafhankelijkheden van multispecies-floreren.

Epilogue

One of my participants described my artefact as "poetic," a comment that deeply touched and delighted me. It perfectly captured something I had hoped to achieve—the creation of a living artefact that, through care, would inspire beautiful and meaningful moments in everyday life.

Like a quiet, subtle poem that seeps into the reader's senses, the artefact evoked emotions and invited introspection. It fostered open-ended engagement, encouraging people to explore their unique, evolving relationships with microbes and the environments they share.

While care can often seem challenging, my artefact sought to reveal another side of care—one that unfolds through small, thoughtful gestures that quietly transform relationships. In this project, those gestures emerged in the delicate interactions between humans and microbes, woven into the rhythm of life, time, and materiality.

As I conclude my thesis and embark on new beginnings, I invite readers to approach care for the more-than-human world with an attitude of poetry. Take joy in the simple acts of noticing, touching, and doing—without rushing or judging. Small, consistent efforts can create meaningful change, both around us and within us.

Appendix

A.1. THE CONSTRUCTION OF THE CYANO-CHROMIC INTERFACE (CHAPTER 4)

In this section, we outline the multiple steps that were taken in the construction of our *Cyano-chromic Interface*, highlighting the multidisciplinary nature of our design processes. We begin by explaining how the cyanobacteria cells were cultured and maintained, followed by how the microbes were integrated as part of the interface fabrication process, involving custom modification of 3D printing machinery. We conclude the section with its assembly steps.

A.1.1. CULTURING AND MAINTAINING CYANOBACTERIA

Synechocystis sp. PCC 6803 cells (Pasteur Culture Collection, France) were cultured in BG-11 medium (pH 7) with trace metal mix solution (Sigma-Aldrich). Cultures were maintained in a biosafety level 1 lab, under a light/dark cycle of 12:12h and an illumination level of approximately 10 µmol · m−2 · s−1, with a white LED light, in a sterile environment (figure A.1).

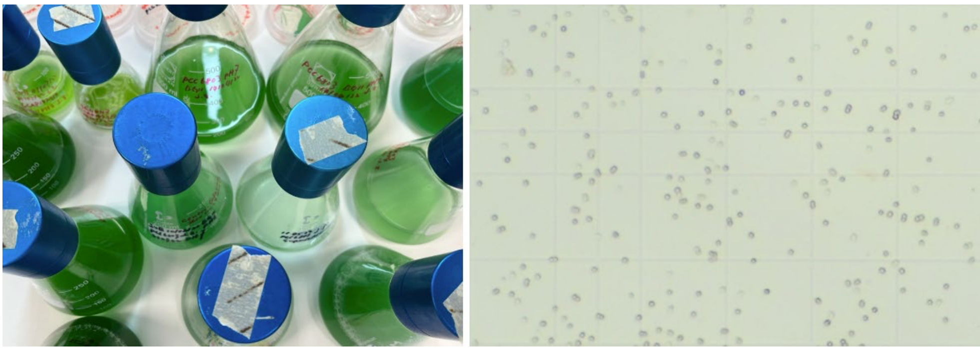


Figure A.1.: *Synechocystis* sp. PCC6803 liquid culture grown for 4-6 weeks (left) and a microscopic image of the cells (100x magnitude) (right)

Interface fabrication was based around the Direct Ink Writing (DIW), an extrusion-based additive manufacturing method, which generally enables custom design configurations of electrodes towards achieving optimal power output. More specifically, we made an additional improvement to an existing method of ink-jet printed paper-based biophotovoltaic (BPV) system [1], a technique that has shown to reduce bulkiness of traditional liquid-reservoir based systems. Here, we used DIW [2] for depositing conductive inks and cyanobacterial culture in the form of bio-ink in our interface, which retains the benefit of ink-jet printing (reducing bulkiness), but also has other advantages. In this method the cyanobacteria become immobilised in hydrogel during the printing process for retaining moisture over a longer period. It also allows for the printing of a wider range of inks of various particle size and viscosity.

1) (Bio)printing. First, anode ink (suspended solution of carbon nanotubes, Nink1000 ink from Nano-lab USA) and cathode ink (Carbon-platinum Uno-ink from FuelCellEarth, USA) were printed onto a piece of copy paper (80g /m2) in sequence, with a modified 3D printer (Creality Ender Pro 3). The inks were loaded onto a syringe with a piston, which was controlled by a modified extruder. Desired patterns with different shapes and sizes were designed and converted into g-codes for the printer to read and execute. The syringe was connected to a print nozzle (OD = 0.97mm) via silicone tubing (ID = 4mm; OD = 6mm). The paper was pasted onto the print bed using a low-tack tape to prevent warping of the paper during printing. An extrusion rate of 3 mL/h was maintained throughout the process of ink printing.

Second, bio-ink containing the cyanobacteria culture was printed onto the anode. The printing needed to be processed within a sterile environment. As such, we designed and constructed a sterile bio-printing cabin for housing the 3D printer and the printing process. Here, we dismounted the hot-end module and replaced it with a liquid extrusion unit consisting of a syringe, a syringe pump, silicone tubing, and a tube holder. Figure A.2 illustrates the overall set up, with its different components and functions. The bio-ink was made using a concentrated pellet of cyanobacteria, which was obtained by centrifuging 50 mL of a 4-6 week old *Synechocystis* sp. PCC6803 culture (spun at 4000 rpm for 5 mins). The concentrated pellet was then resuspended in 5 mL of fresh BG-11 medium. 5 ml of sodium alginate (5 w/v%) was added to the suspension and vortexed as the final step in the bio-ink preparation. Concentration of cyanobacteria cells in this final bio-ink preparation, was measured (using Fuji ImageJ) as

5.65x108cells/ml. An ink-loaded anode paper was pasted over the top of the low tack tape on an acrylic plate, and supplied with 1 drop of calcium chloride (5M). The surface of the ink-loaded paper was flattened with an L-shaped spreader.

Bioprinting was performed using the same modified 3D printer (Creality Ender Pro 3) in our customised sterile cabin. A sterile syringe was loaded with 10 mL of bio-ink and mounted onto a syringe pump. The syringe was connected to a 0.2 mL pipette tip via silicone tubing (ID = 4mm; OD = 6mm). An extrusion rate of 14 mL/h was maintained throughout the printing process.

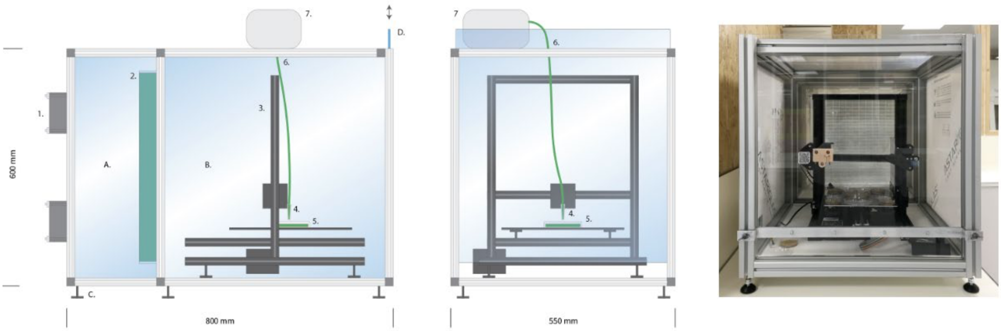


Figure A.2.: Printer cabin design illustration and photograph of the set-up. Main sections: A. back chamber for HEPA filter B. front chamber for printing C. ad- justable feet for levelling D. sliding window for ventilation and operation. Components: 1. Fans for blowing air into the chamber 2. HEPA filter for catching particles from air flow 3. 3D printer 4. Printing nozzle adapted from a D10 pipette tip 5. Plate for print substrate 6. Hole for tubing 7. A syringe pump (details not shown)

2) Electrochromic (EC) Material Preparation. The electrochromic material was made by screen-printing PEDOT:PSS pigment in-between two sheets of ITO coated PET. We followed the instructions shared by Ynvisible, the company that developed the EC material which we used [3].

A.1.3. ASSEMBLY OF A STACKED CYANO UNIT

To assemble the stacked cyano unit, the following components were prepared: 2 pieces of square stainless steel plates (65 x 65 mm), 1 piece of acrylics (65 x 65 mm), 2 pieces of hydrogel sheets (40 x 40 mm), plastic screws, connecting wires, cathode material and printed anode material. Figure A.3 illustrates the stacked cyano unit assembly process.

In this configuration we used off-the-shelf carbon paper loaded with Platinum (purchased from H2Planet Europe) as an alternative for the cathode ink, to simplify the characterization process.

A.2. CARE INSTRUCTION CARDS (CHAPTER 5)

The artefact consists of living cyanobacteria that absorb CO2 from their surroundings and release fresh oxygen. The artefact is a small-scale prototype of a set of future artefacts, that might have different functions, such as purifying air, powering small electronic devices, sensing light and air qualities. In this study, we focus on its air-purifying ability. Thus, you are requested to carry the artefact with you to places where you need slightly more fresh oxygen. For the coming two weeks, you need to keep it alive and healthy for it to maintain its function. Below are a few tips to help in keeping it alive:

1. The artefact prefers medium to bright light, but doesn't like direct sunlight which might cause an increase in temperature and kill the living cyanobacteria.

2. During the day, when the light condition is right, you will notice a purple tint appearing gradually on the artefact, depending on how much light it receives. This indicates the cyanobacteria are doing well. If the light condition is not optimum, the purple tint would fade away gradually. Then you need to create/find the right light condition for the artefact (this doesn't need to be inside your house). Remember, The artefact is robust, you can fold, hang, stick, hide, etc.

3. During the night, the artefact naturally fades its purple tint until the next day when it receives light again. If the cyanobacteria are healthy, their colour becomes greener over 3-5 days.

4. To help you judge your artefact condition, we provide you with a set of colour cards, that shows how it would approximately look like in its best, medium or worst states. You may also use the back of the card (blank) as a background to observe colour change.

Please take a photo of the artefact and its surroundings whenever you notice a change in its colour or if you move it to a new location or change its form (e.g., by folding). I will follow your experience with the cyanobacteria care artefact every 2 or 3 days via WhatsApp/email/or other platforms you prefer. However, whenever you want to share things with us, feel free to chat or send us photos.

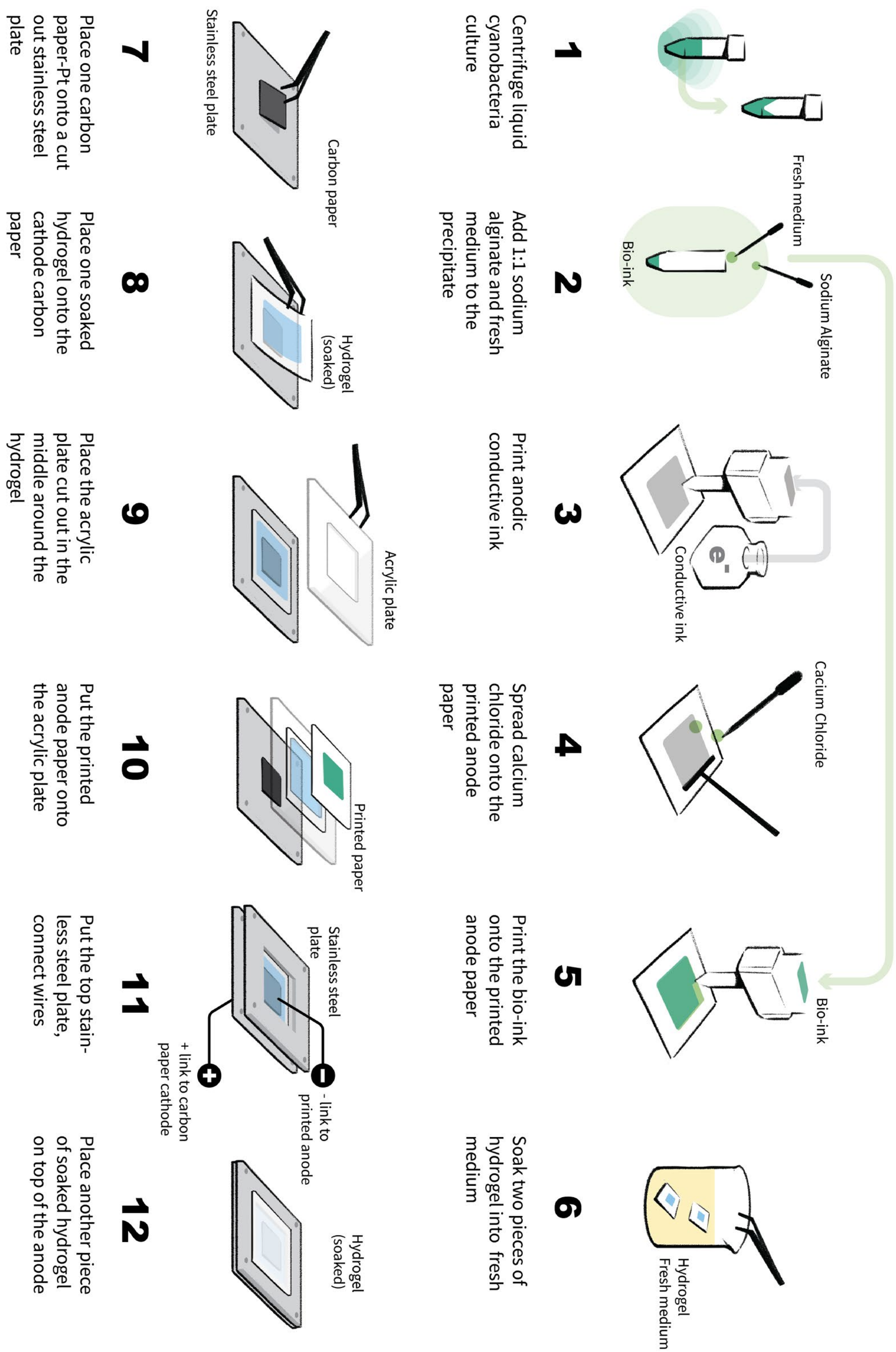


Figure A.3.: Steps involved in stacked cyano unit assembly.

Just a last tip, give a nickname to your artefact.

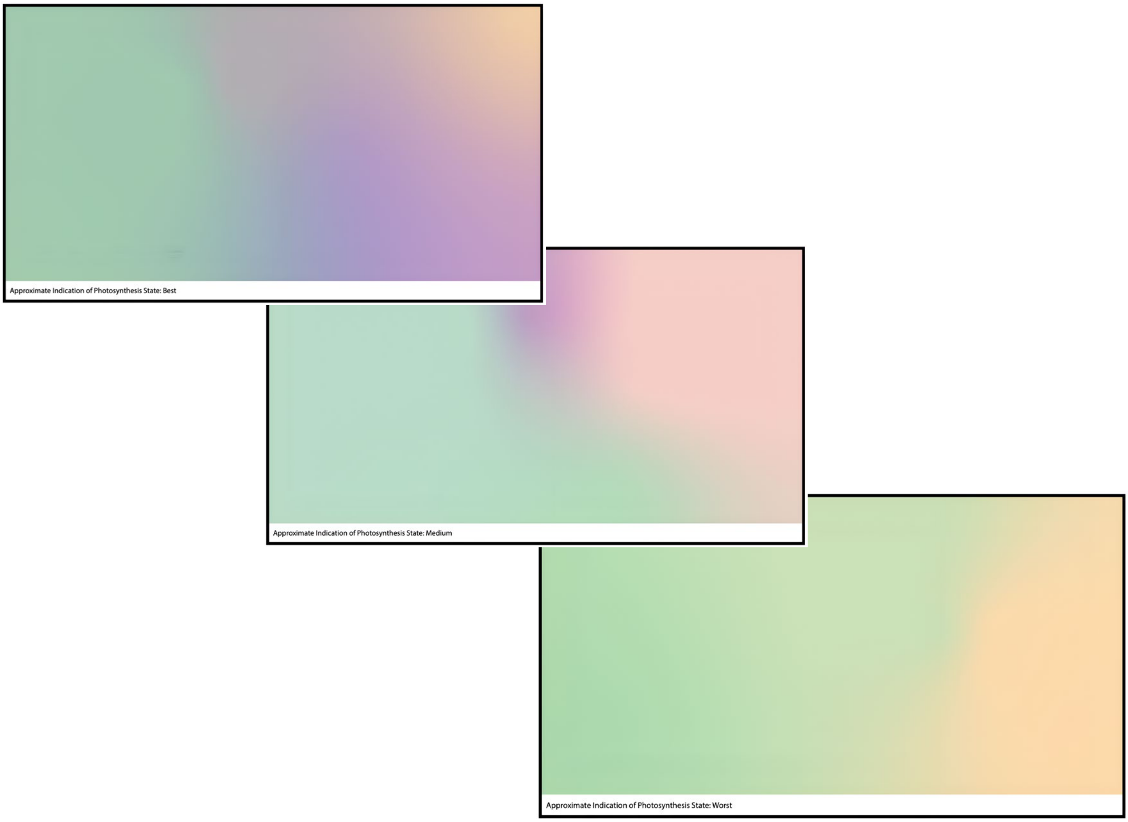


Figure A.4.: Printed cards hand-out to participants with approximate indication of photosynthesis states.

REFERENCES

[1] M. Sawa, A. Fantuzzi, P. Bombelli, C. J. Howe, K. Hellgardt, and P. J. Nixon. "Electricity generation from digitally printed cyanobacteria". In: *Nature communications* 8.1 (2017), pp. 1–10.

[2] E. M. Spiesz, K. Yu, B. A. Lehner, D. T. Schmieden, M.-E. Aubin-Tam, and A. S. Meyer. "Three-dimensional Patterning of Engineered Biofilms with a Do-it-yourself Bioprinter". In: *JoVE (Journal of Visualized Experiments)* 147 (2019), e59477.

[3] Y. I. Inc. Ynvisible. Ynvisible Interactive Inc. 2021. URL: https://www.ynvisible.com/.

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List of Publications

J. Zhou, Z. Doubrovski, E. Giaccardi, and E. Karana. "Living with Cyanobacteria: Exploring Materiality in Caring for Microbes in Everyday Life". In: *Proceedings of the CHI Conference on Human Factors in Computing Systems*. CHI '24. Honolulu, HI, USA: Asso- ciation for Computing Machinery, 2024. ISBN: 9798400703300. DOI:10.1145/3613904.3642039. URL: https://doi.org/10.1145/3613904.3642039

J. Zhou, R. Kim, Z. Doubrovski, J. Martins, E. Giaccardi, and E. Karana. "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/10.1145/3563657.3596132

R. Kim, **J. Zhou**, E. G. Groutars, and E. Karana. "Designing living artefacts: Opportunities and challenges for biodesign". In: *DRS2022: Bilbao*. DRS2022. Design Research Society, June 2022. DOI: 10.21606/drs.2022.942. URL: http://dx.doi.org/10. 21606/drs.2022.942

J. Zhou, B. Barati, E. Giaccardi, and E. Karana. "Habitabilities of living artefacts: A taxonomy of digital tools for biodesign". In: *International Journal of Design* 16.2 (2022), pp. 57–73. DOI: 10.57698/v16i2.05. URL: https://doi.org/10.57698/v16i2.05

J. Zhou, B. Barati, J. Wu, D. Scherer, and E. Karana. "Digital biofabrication to realize the potentials of plant roots for product design". In: *Bio-Design and Manufacturing* (2020). ISSN: 2522-8552. DOI: 10.1007/s42242- 020-00088- 2. URL: https: //doi.org/10.1007/s42242-020-00088-2

About Me

I was born and grew up in Sichuan, China, a region known for its unique culinary cultures and landscapes shaped by mountains and rivers. Life there was laid-back. I have been away from my hometown for twelve years. While drifting through different places and cultures, with me I carry that ease of my home place.

My parents, both scholars in applied biology, nurtured my first curiosity about our interactions in the living world. As a child, I was introduced to fascinating beings—like the *Lagerstroemia indica*, a tree that shivers when tickled. I tickled *Lagerstroemia indica* everytime I encountered one—perceiving them as active beings responding to their environments just like me. Weekends were spent making leaf skeleton bookmarks, tiny windows into the intricate structures of plants. After school, I often waited for my mother in her biology lab, where she showed me agar plates and flasks with little cultures in them. I was mesmerized by these delicate glass containers and the invisible worlds they held.

Since young, I was introduced to the ancient Chinese philoshpphy of Taoism at school. I was facsinated by the worldviews shared by Taoist philosophers. Particularly, the thoughts of Zhuangzi, existing as anecdote, metaphors, fabulations, poetic, narrative expressions of stories, conversations and phenomenon. As early as 369-286 BC, he criticised the "status quo" and proposed ideas of being and doing that are still highly valuable today—such as living as one with nature and celebrating the "way", a state of being without too much intension to control. Learning fragments of his thoughts, I developed my earliest worldviews through an elder's wisdom, which has quietly accompanied me through my growth over years.

Moving to the Netherlands to study and research has been a chance to not only experiment and explore new knowledge but also introspect my cultural philosophical roots. Having started combining design and biomaterials in my undergraduate studies, I was drawn to the ethos of Dutch design practitioners to explore more sustainable and eco-friendly futures of designing with the living world. Growing as a design researcher, I had great honor to have learnt from excellent scholars from design, biology and the feminist care, posthumanism theories. I also increasingly realized that the deep Taoist influence in me has been evoked through engaging with western modern scholarship. Towards the end of 2024, I talked to Joshua Konkankoh in a design symposium, who is a Cameroonian indigenous elder and social entrepreneur who combines regenerative education, permaculture, and environmental leadership to reduce social inequalities. I asked Joshua, "You've criticised the ways of knowing in western socieities, so what is still lacking there?"

"Elders," he said, "people who tell the wisdom of living and being with nature from generation to generation." I was stunned for a moment, then immediately found resonance—reminded of my ongoing refleciton upon my own cultural and philosophical root. I was touched, and opened up on some uneasiness I experienced when I had to "unlearn" and "relearn" worldviews and beliefs built upon the western way. He nodded, and said lightly—just remeber who you are. He repeated it once again.

Simple, light but heavy words. That was the moment when I realized that my positionality is not just scholarly but also cultural, philosophical, historical and geo-political, amidst the experience of the western superiority that many other cultures share. My positionality is a source of richness and strength; I want to bring it to the forefront—to embrace ways of knowing that are more oriented to phenomenal, perceptual, metaphorical, sentimental, anecdotal, poetic and holistic. Having not fully explored this positionality, as my career as a researcher continues, I hope to contribute an alternative voice that is culturally disruptive to challenge Western-centered ontologies and epistemologies of being.

Curriculum Vitae

EDUCATION

2024	PhD, Industrial Design Engineering Delft University of Technology, the Netherlands.
2019	MSc. Design for Interaction Delft University of Technology, Delft, the Netherlands
2017	BEng. Industrial Design Tongji University, Shanghai, China

EMPLOYMENT AND AFFILIATIONS

2019 – 2024	Delft University of Technology, Delft, Netherlands PhD, Materials Experience Lab Junior Researcher, Materials Experience Lab
2020 –	Studio Jiwei (self-employed), Rotterdam, Netherlands Materials Design & Research
2019	Studio Wieki Somers, Rotterdam, Netherlands Design and Research Internship
2018	Mediamatic, Amsterdam, Netherlands Biodesign Internship
2016	Neuni Group, Shanghai, China Materials Research Internship

TEACHING & SUPERVISION

Teaching

2023	MSc. Industrial Design Engineering Delft University of Technology, Delft, Netherlands Guest Lecturer, Fundamentals of Biodesign
2022	MSc. Industrial Design Engineering

	Delft University of Technology, Delft, Netherlands
	Project Design & Lecturer, Designing Living Artefacts
2022	MSc. Industrial Design Engineering
	Delft University of Technology, Delft, Netherlands
	Project Owner & Material Expert, Material-Driven Design
2021 – 2025	MSc. Industrial Design Engineering
	Delft University of Technology, Delft, Netherlands
	Guest Lecturer, Material-Driven Design

Supervision

2020 – 2023	Murui Du (BEng. Product Design, Tongji University)
	Yin Zhou (BEng. Product Design, Tongji University)
	Keer Hu (BEng. Product Design, Tongji University)
	Wenxuan Xi (MSc. Media Arts and Technology, Leiden University)
	Neva Linn Rustad (MSc. Design for Interaction, TU Delft)
	Sylvia Ko (MSc. Integrated Product Design, TU Delft)

EXHIBITIONS & TALKS

Exhibitions

2023	Dutch Design Week
	Project: *Soiled*
2022	Dutch Design Week
	Project: *The Tea Recipes*
2021	CHA CYCLE, Amsterdam
	Project: *The Tea Recipes*
2020	Hyper Rhizome, Amsterdam
	Project: *Interwoven*
2020	Matter Matters, Hong Kong
	Project: *Interwoven*
2018	Craft the Reset, Shenzheng
	Project: *The Tea Recipes*

Talks

2023	Dutch Design Week, Design United
2023	DIS23 (Designing Interactive Systems) workshop "Designing with the more-than-human: Temporalities of thinking with care"
2022	DRS conference conversations "Designing living artefacts: Opportunities and challenges for biodesign"
2021	Twente Sustainable Design Week
2020	Circular Experience

TECHNICAL SKILLS

Electronics	Arduino IDE
Fabrication	3D Printing, Bioprinting, Laser cutting, CNC, Bio-based materials, Screen printing, Electrochromic materials
Software	Adobe Creative Suite, Final Cut Pro, Rhino, Cinema4D, Blender
Lab Operation	Chemical lab, Materials Lab, Biological lab

PUBLICATIONS

Peer-Reviewed Journal & Conference Papers

[P4] **Zhou, J**., Doubrovski, Z., Giaccardi, E., & Karana, E. (2024, May). Living with Cyanobacteria: Exploring Materiality in Caring for Microbes in Everyday Life. In Proceedings of the CHI Conference on Human Factors in Computing Systems (pp. 1-20).

[P3] (Best Paper Honourable Mention) **Zhou, J.**, Kim, R., Doubrovski, Z., Martins, J., Giaccardi, E., & Karana, E. (2023, July). Cyano-chromic interface: Aligning human-microbe temporalities towards noticing and attending to living artefacts. In Proceedings of the 2023 ACM Designing Interactive Systems Conference (pp. 820-838).

[P2] **Zhou, J.**, Barati, B., Giaccardi, E., & Karana, E. (2022). Habitabilities of living artefacts: A taxonomy of digital tools for biodesign. International Journal of Design, 16(2), 57-73.

[P1] **Zhou, J.**, Barati, B., Wu, J. et al. Digital biofabrication to realize the potentials of plant roots for product design. Bio-des. Manuf. 4, 111–122 (2021).

https://doi.org/10.1007/s42242-020-00088-2

Short Papers

[S1] Kim, R., **Zhou, J.**, Groutars, E. G., & Karana, E. (2022). Designing living artefacts: Opportunities and challenges for biodesign.

Book Chapters & Articles

[B1] **Zhou, J.** (2023). Potential of Being a Sustainable Material In E.J. Sam, Mainstudio (E. van Gelder), D. Scherer (Eds.), Interwoven: Exercises in Root System Domestication (pp. 189-190). Jam Sam Books.

Theses & Dissertations

[T2] Zhou, J. (2024). Mattering More-than-human Care in Biodesign [PhD dissertation, Delft University of Technology, Netherlands].
[T1] Zhou, J. (2019). Interwoven: Designing biodigital objects with plant roots [9.5/10 Master Thesis, Delft University of Technology, Netherlands].

RESEARCH FUNDING

Project: *Soiled*
Principle Investigator: Gizem Oktay, Eindhoven University of Technology; Jiwei Zhou, Delft University of Technology; Dienke Stomph, Wageningen University, Netherlands
Funding: € 4,000 (collective)
Funding Bodies: 4TU Federation
Duration: July 2023 – October 2023
Related Exhibition: Dutch Design Week 2023

OTHER SCHOLARLY ACTIVITIES

Workshops

2023	SOILED: Forging new relations between humans and soil bodies Eindhoven, Netherlands
2022	Bioprinting Delft, Netherlands

2023 Kitchen Bio-futures
Arcelik, Istanbul, Turkey

Peer Review
ACM HCI JOURNAL (2023)
IASDR (2023)
TEI (2025)
CHI (2025)
DIS (2025) AC (RtD paper track)

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