Shaping Ecological HCI through Materials Design and Fabrication: A Review and Future Design Considerations

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Ecological HCI (EHCI) centers on interactive technologies that are *aware of* and *integrated with* ecological systems and principles. Introduced at CHI 2024, it highlights emerging nature-centered studies and seeks to expand the scope of Sustainable HCI through a more-than-human perspective. However, as a new concept, it faces several challenges, including a lack of systematic summarization and comparisons of existing approaches. To this end, we conducted a literature review focused on materials design and fabrication, which can directly affect the production, consumption, and applications of EHCI. We review 45 articles, providing an overview of the state-of-the-art studies, and propose a taxonomy and design framework to guide future practices. Additionally, we synthesize key discussions from CHI 2024 that contribute to shaping the concept of EHCI. This study serves as a first review of EHCI and offers insights into how existing studies can provide references for future development in EHCI.

CCS Concepts: • **Social and professional topics → Sustainability**; • **Human-centered computing → Interaction design process and methods**; **HCI theory, concepts and models**.

Additional Key Words and Phrases: Ecological HCI, Sustainability, Materials design and fabrication, Sustainable HCI, Literature review

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1 INTRODUCTION

The ecological crisis is one of the greatest challenges humanity faces this century, for climate change and ecosystem degradation threaten the future of lives on earth [118]. As the concept of sustainability gains increasing public attention, a growing body of academic and industrial studies in human-computer interaction (HCI) have begun to focus on exploring how interactive technologies can advance environmental sustainability and address the ecological challenges we are facing. Through these efforts, HCI researchers want to technically better understand and tackle the complexity of sustainability, which is regarded as a social-technical problem [102]. As relevant HCI practices progress, the concept of sustainability has been constantly evolving and iterating [92]. For example, sustainable interaction design (SID) [22, 103] was first put forward at CHI 2007 as a starting point for the sustainable transition in the HCI field, to encourage interaction designers to make informed choices based on the concepts of use, reuse, and disposal. As the field matured and expanded, it turned into what we now call Sustainable HCI (SHCI), summarized by DiSalvo et al. [44] at CHI 2010. After the proposal of SHCI, an increasing amount of workshops have been organized at top-tier conferences in the HCI field (e.g. CHI, UIST). For example, related workshops discussed the design patterns, principles, strategies [81] and evaluation approach for SHCI [126], sustainability challenges and opportunities associated with self-powered and sustainable interfaces and interactions [105], and rapid prototyping [162]. However, the development of Sustainable HCI (SHCI) over the past decade reflects the understanding of sustainability at that time, highlighting the need for a broader perspective [127]. In response, the concept of Ecological HCI (EHCI) was introduced in a special interest group (SIG) at CHI 2024. EHCI seeks to expand the current framework of SHCI by adopting a nature-centered and more-than-human approach, representing a significant milestone in HCI that addresses broader ecological concerns rather than solely focusing on human-centered sustainability issues [92].

However, EHCI faces several challenges that researchers must address for its future development, including (1) redefining its broad goals, (2) determining its positioning within the HCI landscape, (3) establishing a systematic summarization and comparison of existing approaches, (4) specifying evaluation methods and metrics, and (5) conducting field testing to assess long-term impacts [92]. These discussions and challenges have motivated us to undertake a literature review aimed at clarifying the concept of EHCI and assisting HCI researchers in drawing inspiration from existing studies to guide future developments in this emerging field.

As EHCI was proposed based on SHCI, both of them focus on environmental sustainability, encompassing common study topics such as materials design and fabrication. This topic has the potential to help solve problems related to environmental sustainability to promote ecological well-being, whether in the design, fabrication, or application process. However, researchers have realized there exists challenges, such as the lack of a systematic design approach guidance[104].

Tapping into this, we aim to systematically summarize, categorize, and compare existing materials design and fabrication studies and approaches in order to develop a taxonomy and framework that can guide future practices in EHCI. By doing so, this study specifically addresses one of the previously mentioned challenges in EHCI, namely the lack of systematic summarization and comparison of approaches [92]. We first summarize the discussions of EHCI during the SIG at CHI 2024. Then, we conduct a literature review of 45 studies (Fig. 1), to provide an overview of the state-of-the-art studies, as well as propose a taxonomy and design framework for future materials design and fabrication practices to facilitate the development of EHCI.

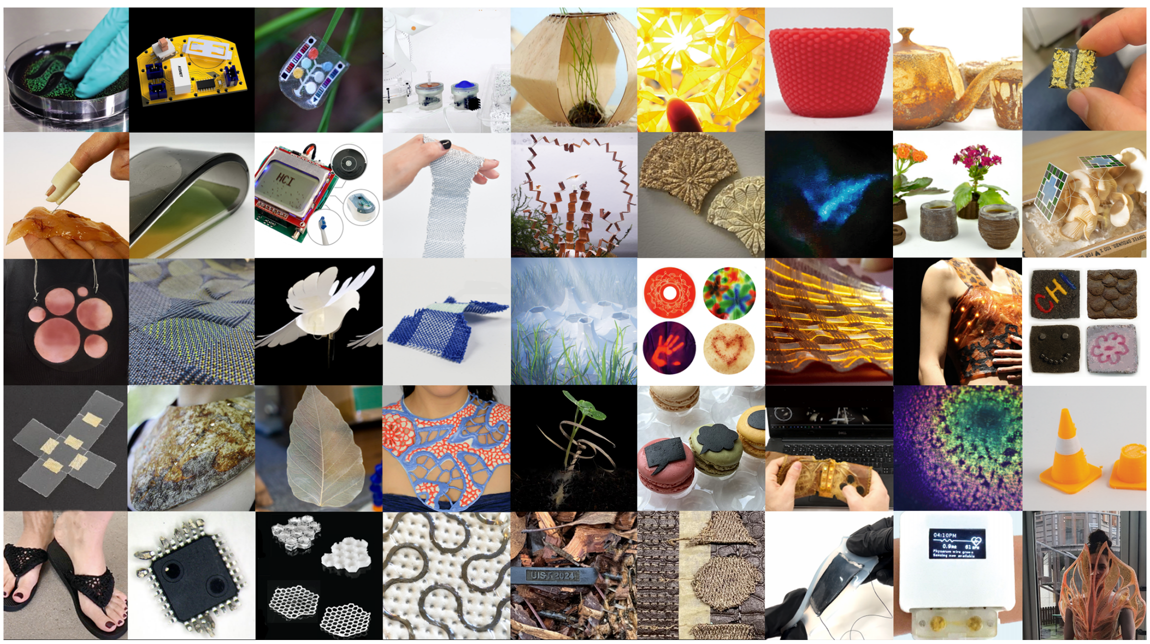

Fig. 1. Materials design and fabrication cases with environmental sustainability considerations for future development of EHCI in this literature review. Figures are reproduced with permission.

The main contributions of this work are:

(1) An overview of the state-of-the-art materials design and fabrication studies with environmental sustainability considerations in HCI.
(2) A taxonomy to systematically categorize the materials, fabrication methods, and their problem-solving from sustainable and ecological perspectives in the included studies to help HCI researchers understand how the

existing studies were conducted under the scope of SHCI and how they can provide references for future development of EHCI.

(3) A design framework to support future practices to facilitate the development of EHCI while analyzing state-of-the-art studies from a system perspective and comparing current approaches of materials design and fabrication in HCI field.

2 RELATED WORK

2.1 From SID, SHCI to EHCI: Re-diversifying Sustainability in HCI

In HCI, sustainability serves as an increasingly important topic in both research and practice, highlighting the significant impact of technology on the environment and social equity [96, 102]. As mentioned, the concept of sustainability in the HCI field undergoes three remarkable transitions: from SID to SHCI, then EHCI. In this section, we aim to provide a clear introduction of the concept of EHCI and its relationship with SHCI.

2.1.1 Definition, Scope and Challenges of EHCI.

EHCI aims to study, design, and evaluate interactive technologies that are aware of and integrated with ecological systems and principles [92]. In analyzing how EHCI emerges from SHCI, we refer to the Sustainable Development Goals (SDGs) [83]. SHCI mainly concentrates on achieving the goal of Responsible Consumption and Production, which shows that the research scope of SHCI for the last decade has been too narrow [64]. However, recent study trends demonstrate a significant growth in developing energy-harnessing devices [96], monitoring environmental conditions [69], facilitating the conservation of environmental status [34], and catalyzing the restoration of environmental damage [98]. The aforementioned cases showcase an ecological perspective and strong interrelation with the environment, which has inspired researchers to expand SHCI to EHCI while trying to achieve more of the SDG goals, such as Affordable and Clean Energy, Life On Land, Climate Action, Life Below Water, etc. [92].

However, as EHCI is an emerging concept in HCI, it has challenges for future development, such as (1) a need to refine EHCI's broad goals, (2) a need to better position EHCI within the broader field of HCI, (3) a lack of systematic summarization and comparison of approaches, (4) a lack of specific evaluation methods and metrics, and (5) a lack of field testing to evaluate long-term impact [92].

2.1.2 Clarification of the Relationship between SHCI and EHCI.

To better differentiate between SHCI and EHCI, we refer to Fig. 2 to introduce the relationship between SHCI and EHCI. SHCI focuses on social, economic, and environmental sustainability [24, 48, 119], consisting of various genres, including sustainable interaction design (SID) [25, 44]. It has focused on exploring how digital technologies raise awareness and foster a more sustainable lifestyle and how behavior among individuals can help tackle the environmental crisis [106, 119], embodying a human-centered approach [44]. Viewed from the environmental sustainability perspectives, mainstream SHCI studies mostly focus on the recyclability [90], reusability [65], and degradability [12, 139] of interactive technologies. These studies primarily relate to SDG 12, indicating a narrow focus in current SHCI research. This limited scope calls for solutions to more complex environmental sustainability issues while grappling with the full multi-scalar complexity of sustainability challenges. [38]. As mentioned, emerging research has expanded into designing interactive technologies that embrace an ecological perspective and innovating with a higher degree of consciousness of environmental sustainability, such as [34, 69, 98]. In view of this, EHCI was proposed to expand the scope of SHCI [92], shifting from a solely human-centered design approach to a nature-centered and more-than-human design approach [92].

This approach emphasizes "making with the environment" [146] and de-centering the role of human while highlighting the role of larger ecosystems [57]. Therefore, EHCI is not meant to replace SHCI, but to complement SHCI and provide a different lens through which we can approach sustainable transition and innovation.

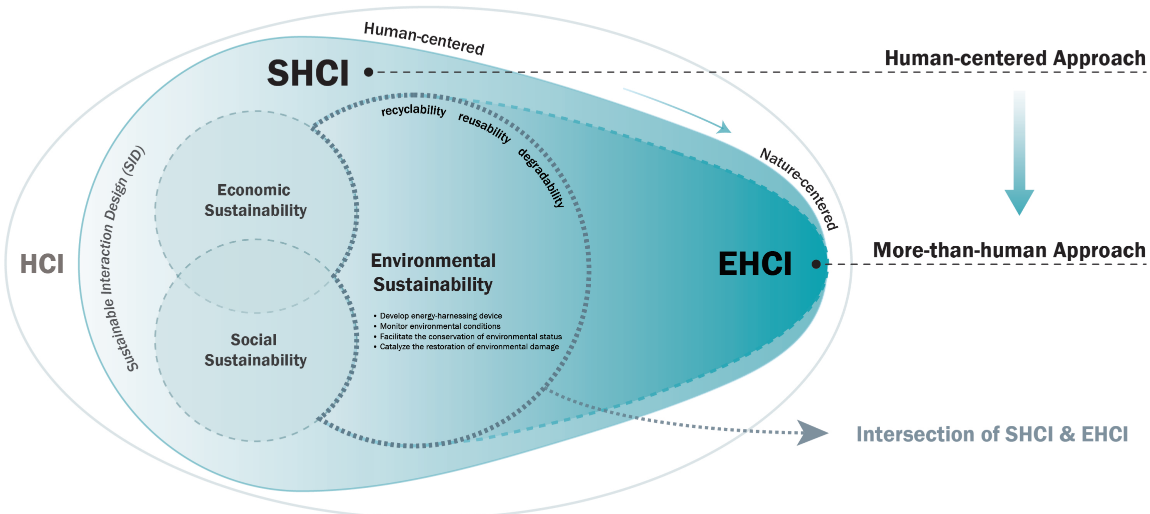

Fig. 2. The relationship between SHCI and EHCI: EHCI aims to expand the current scope of SHCI with a nature-centered and more-than-human design approach.

2.2 Materials Design and Fabrication Towards Sustainability in HCI: Current Practices, Challenges, and Future Directions

In recent years, a growing number of HCI researchers have shared a common consensus that materials play an active role in the development of dynamic relationships between humans and interactive systems [59, 72, 133, 169]. They have commenced studies on how to explore materials earlier in the design process [51, 56, 149], leveraging the different properties of materials to fabricate innovative artifacts and prototypes, thereby unleashing humans' interactive potential [123].

Investigating materials studies in HCI from sustainability-related perspectives, research trends have revealed a potential consensus on positioning the material studies in the HCI field at the ecosystem and more-than-human level. Bennett [21] proposed that the researchers should rethink "how matter comes to matter", and new materialism recognizes the material world not as a silent backdrop or inert stage upon which human activity unfolds, but as a vibrant field where active processes of significance are continually unfolding within ecosystems. Moreover, Giaccardi et al. [57] recognized the rethinking of how materials are conceptualized and engaged within HCI as an important issue of more-than-human design and HCI.

In response to the growing considerations of sustainability in HCI, more practices of materials design and fabrication towards sustainability have been demonstrated by HCI researchers [19], mainly focusing on sustainable applications of materials and fabrication of novel interactive devices for sustainability. Bell et al. [19] introduced the applications of bio-based materials, such as ReClaym (a clay-like material made from compost) [18], Alganyl (an algae-based bioplastic) [15], Dinoflagellate (an algae that emits bioluminescent light) [113] and SCOBY (a bacterial and yeast symbiotic culture in kombucha) [17]. Zhu et al. [172] fabricated EcoThreads to integrate conductive threads into biodegradable textiles through various fabrication methods to advance the sustainability of e-textiles. Yao et al. [164] utilized natto cells as nanoactuators for humidity-responsive materials through manual pipetting, inkjet printing and atomizing fabrication techniques to advocate for bio-responsive materials in HCI. Nicolae et al. developed biohybrid devices [111] based on bacterial cellulose cultivation and electronic devices development, incorporating various fabrication techniques such as carbonization and laser cutting. Cheng et al. [36] utilized polyvinyl alcohol and liquid metal to fabricate recyclable, modular electronic devices that dissolve in water, highlighting the potential for sustainable lifecycle management in electronics. Yan et al. [163] introduced 3D-printed detachable housings for PCB prototypes, enabling reusable and solderless component assembly, which reduces material waste in rapid prototyping.

Current practices have already shown early attempts at designing and fabricating interactive prototypes with materials towards sustainability in HCI, however, limitations still exist in this field which provide opportunities and directions for future research. Through literature review and analysis, the following common challenges that need future work are identified as: (1) the need for analyzing and summarizing existing cases in different genres with one coherent taxonomy or framework [138], (2) the need for clearly identifying the sustainability-related problems solved in each case and making real impact on the environmental sustainability of the ecosystem [64], and (3) the need for building up or optimizing systematic, productive and useful methods to guide HCI and design practices [81, 127, 137, 138], especially in the emerging field of material design and fabrication towards sustainability [104] and EHCI.

2.3 Approaches of Materials Design and Fabrication in HCI

A growing number of HCI and design researchers have realized the significance of developing a framework to guide materials research in HCI and put it into real practice. Early explorations of developing design concepts and approaches originated from a human-centered design perspective, focusing on how users experience the sensorial features of materials and the way to design for materials experiences in human-material interaction. In 2013, Karana et al. [76] systematically proposed the concept of "materials experience" as the fundamentals of materials and design, which acknowledges the experience people have with and through materials [76], highlighting the significant role of materials in shaping people's internal dialogues and interactions with artifacts [74]. To better elucidate the intricate relationship between people, materials and practices, Giaccardi and Karana [56] introduced the concept of "materials experience" within the realm of HCI in 2015, which contributes to the HCI community by articulating a framework for materials experience that discussed how materials shape doing, design practice, and how this is rooted in the experience of them [56].

In order to provide a method to facilitate designing for materials experience, material-driven design (MDD) was put forward in 2015 by Karana et al. [73] to support designers in structuring, communicating, and reflecting on their actions in bridging technical and experiential aspects of materials when materials are departure points in the design process [104]. The MDD method encompasses four main steps, including (1) understanding the materials: technical and experiential characterization, (2) creating the materials experience vision, (3) manifesting materials experience patterns, and (4) designing material or product concepts. The MDD method has been actively applied in the HCI field. For example, McQuillan and Karana [104] recognized multimorphic textile-forms as a material-driven design approach for HCI. Buso et al. described weaving textile-form interfaces as a material-driven design journey [28]. Vogel et al. [157] presented tools for embedding circular thinking in MDD for HCI. Ribul et al. [128] proposed material-driven textile design (MDTD) to design circular material-driven fabrication and finishing processes in the materials science laboratory.

Some noteworthy early attempts are adopted to guide the practices of materials design and fabrication for sustainable transition in HCI with a systematic design method specifically. As MDD urges designers to raise critical questions such as "In which contexts would the material make a positive difference?" [104], it also shows potential in guiding the sustainability research in HCI, such as the cases of biofoam [87] and waste-based materials [42]. However, the range of works explicitly connecting this method in HCI or interaction design is relatively few [104] and the gap remains between theory and practice [127]. Patel et al. [117] developed a pipeline for the design and engineering of sustainable morphing matter; however, this approach is limited to only one kind of material rather than a generalizable approach that can be applied to common practice. Therefore, to sustainably transition from present to future practices, it is significant to propose a design method to broadly support researchers in materials design and fabrication practices towards EHCI.

To bridge the research gaps and address the challenges faced by EHCI, we aim to answer the following review question:

> **RQ:** How can we systematically summarize, categorize, and compare the existing materials design and fabrication studies and approaches to develop a framework to guide future practices in the field of EHCI?

3 METHODOLOGY

We follow the PRISMA protocol (Fig. 3) to ensure rigor in our review of the existing literature.

3.1 Paper Search Design

As this literature review study is positioned in the HCI field, the paper search was conducted in ACM Digital Library, focusing on five top-tier conferences: CHI, UIST, DIS, TEI, Ubicomp, and journals: TOCHI, IMWUT. The search process was conducted from 18th July 2024 to 19th July 2024. The search terms searched in the abstract and keywords are divided into three categories: 1) material-related, 2) fabrication-related, and 3) sustainability-related terms. The authors put the following combination of keywords into the search box in the database: (“material” OR “material design” OR “material-driven design” OR “materiality” OR “shape-changing interface” OR “tangible interface” OR “morphing matter” OR “textile” OR “wearable” OR “actuator” OR “living artifact” OR “bio-design”) AND (“fabrication” OR “digital fabrication” OR “craft” OR “manufacturing” OR “3D printing” OR “4D printing” OR “laser cutting” OR “CNC” OR “rapid prototyping”) AND (“sustainability” OR “sustainable” OR “environmental” OR “ecological” OR “biological” OR “green” OR “energy-harvesting” OR “energy-saving” OR “biodegradable” OR “more-than-human” OR “regenerative” OR “nature-inspired” OR “nature-centered” OR “bio-inspired”).

3.2 Inclusion and Exclusion Criteria

The inclusion criteria of this study were: (1) studies written in English; (2) studies published in peer-reviewed journals or conferences (including extended abstracts such as late-breaking work studies) after 2007, for the CHI 2007 conference in many aspects represented the starting point of systematically thinking about environmental sustainability in the HCI field [64]; (3) the study must use materials to design and fabricate certain prototypes that can help solve problems related to environmental sustainability, no matter their design, fabrication, or application stages; (4) the study must conduct testing of the prototype. The authors excluded ineligible literature that include: (1) review studies; (2) workshops, special interests groups and studio proposals; (3) irrelevant topics such as developing new machines or tools to assist the design and fabrication process.

3.3 Study Selection and Data Collection

Following the search terms, 42 studies were identified from the aforementioned conferences and journals. In order to ensure the completeness of the relevant studies, the authors manually searched and cross-referenced 47 related studies that were missing in the automatic searching process in the database. Therefore, 89 studies were included in the study selection process in total. From these, 45 eligible studies were included following the PRISMA protocol, inclusion and exclusion criteria. The screening process was performed by two independent authors respectively using Zotero software in the following order: to screen the (1) title, (2) abstract, and (3) full paper. The final discussion ensured the two authors achieved a consensus on the excluded studies. The whole process is reported in the PRISMA flowchart shown in Fig. 3.

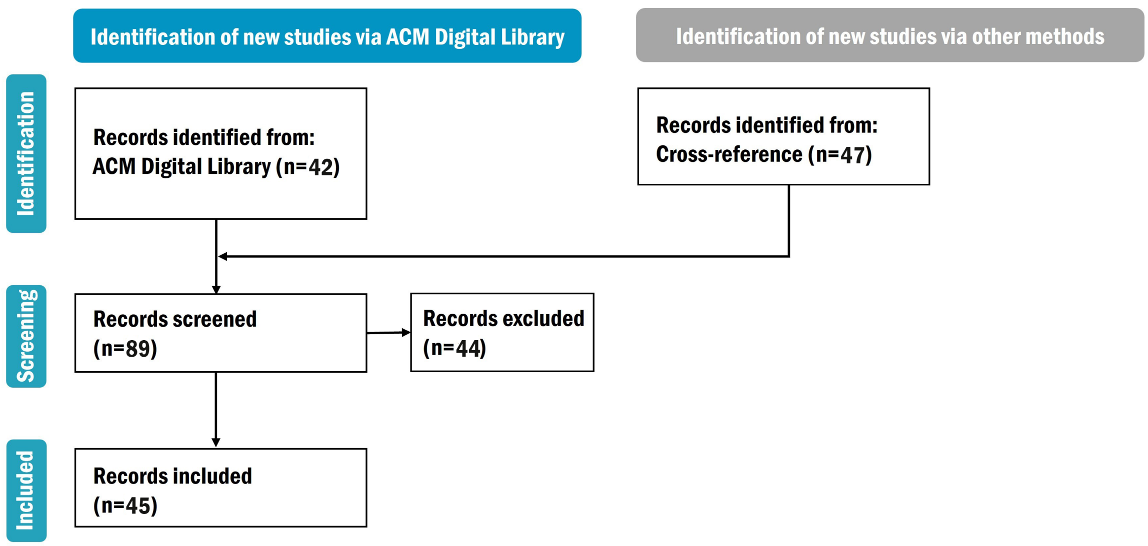

Fig. 3. PRISMA flow diagram of this literature review.

3.4 Quality Assessment

To assess the quality of the selected studies, the authors considered the citation impact of the qualified studies using Google Scholar to obtain the total citations to date and then calculated the Average Citation Count (ACC), which is the "total citations to date" dived by "lifetime (published year till now)" [43]:

$$Average\ Citation\ Count(ACC) = \frac{Total\ Citations\ to\ Date}{Lifetime} \tag{1}$$

4 RESULTS

4.1 Quantitative Overview of State-of-the-Art Materials Design and Fabrication Studies with Environmental Sustainability Considerations

This literature review covers studies published from 2007 to 2024. The number of the included studies has increased significantly over time (Figure 4). In the 12 years from 2007 to 2018, there were few publications, with only one published in 2015, the same year when the SDGs were put forward by the UN. However, in the following years, the number of publications showed an upward trend with a greater increase, especially after 2022. The number of publications peaked in 2023, with 16 studies published.

We also demonstrate the distribution of the publication venues (Figure 4). Studies published at the CHI Conference have the most obvious upward trend and account for the highest proportion among all HCI conferences, accounting for 44.4%, 31.3%, and 50.0% in 2022, 2023, and 2024, respectively.

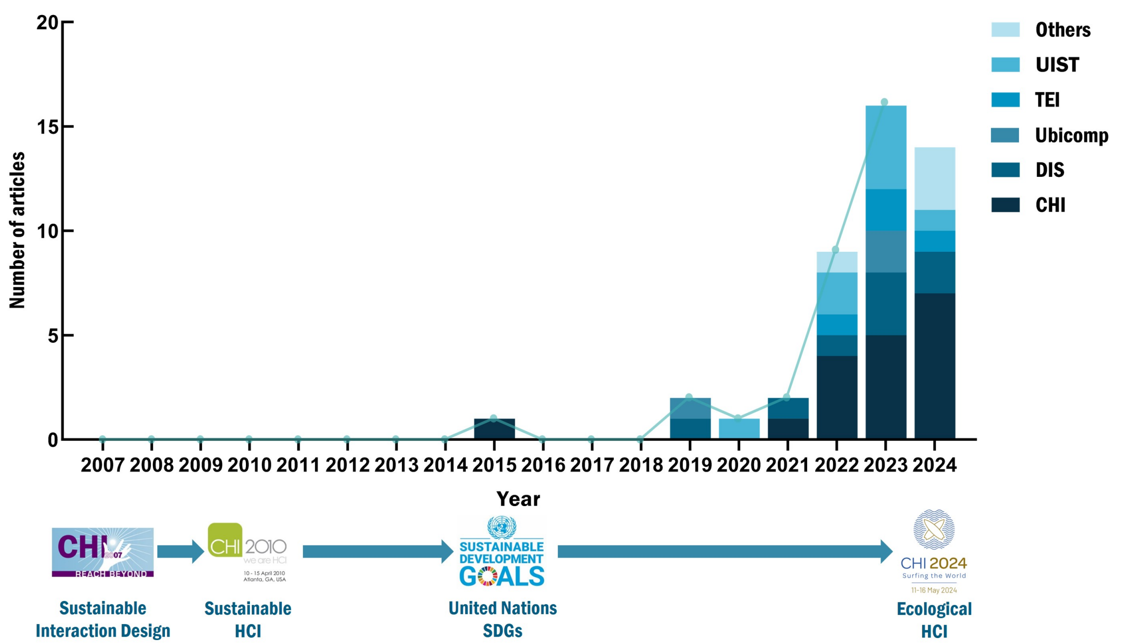

Fig. 4. Publication trends of materials design and fabrication research with environmental sustainability considerations in the HCI field from 2007 to 2024.

As for the overall quality of the included studies, the average, median, and standard deviation of the ACC of the included studies in this literature review are 9.3, 6, 9.0 respectively, ranging from 0 (mainly because the study was published in the year 2024) to 27.4. The result indicates the overall selection had a good impact in the related field despite several low-impact but highly relevant studies. The detailed ACC of each included article can be found in Appendix A.

In the analysis of the cases introduced in the included articles, we extracted 46 materials and 53 fabrication techniques. Regarding the problems being solved in each case, we mapped them to the SDGs from a sustainability perspective. Finally, we found that SDG 7 (Affordable and Clean Energy), 9 (Industry, Innovation and Infrastructure), 12 (Responsible Consumption and Production), 13 (Climate Action), 14 (Life below Water), and 15 (Life on Land) were targeted in the included studies, while the most frequent mentioned are SDG 9 (28.6%) and SDG 12 (47.6%).

Following the fundamental analysis from quantitative perspectives, we propose a taxonomy instead for materials design and fabrication with environmental sustainability considerations to categorize the aforementioned information systematically and clearly in the next subsection.

4.2 Taxonomy of Materials Design and Fabrication Studies with Environmental Sustainability Considerations: Summarization of How Studies Move towards EHCI through Categorization

The taxonomy shown in Fig. 5 is a four-layered and three-dimensional framework. The four layers classify (1) dominant and emerging materials, (2) current fabrication methods used in the included 45 studies, (3) problem-solving mapped to the SDGs, and (4) problem-solving for ecological purposes, indicating the relationship between the sustainable perspective (e.g., SHCI) and ecological perspective (e.g., EHCI) respectively.

4.2.1 Layer 1: Materials.

We classified the materials used in 45 included studies into five categories based on the relevant classification framework adopted by Lee et al. [145] and Duarte Poblete et al. [120]: (1) biosynthetic material, (2) renewable material, (3) biofabricated material, (4) waste-based material, and (5) other material.

- **`Biosynthetic Material`**: refers to polymeric material that is either entirely or partially composed of compounds derived from living organisms [145]. There are 8 materials (16.3%) considered biosynthetic materials. Biofoam, a polymeric foam derived from vegetable oils and other natural sources [50], is eco-friendly, water-soluble, and biodegradable. It reduces the burden on the environment, and promotes ecological cycles and biodiversity through its ability to return naturally to the soil [86, 87].
- **`Renewable Material`**: is made of natural resources that can be replenished quickly, generation after generation [47, 120]. It can maintain the resources from the environment so as to overcome the degradation of natural environmental services and diminished productivity [79]. 9 materials (18.4%) are classified as renewable materials. For example, sodium alginate is renewable and can be used to create sustainable shape-changing interfaces, solving the unsustainable problem of traditional materials [110]. Play-dough is biodegradable, recyclable, repairable, as well as extrudable and structurally stable during the printing process [27].
- **`Biofabricated Material`**: is made by growing living cells and microorganisms such as bacteria, yeast, and mycelium [145]. 13 materials (26.5%) are classified as biofabricated. Cyanobacteria, identified as a rich source of biologically active compounds [2], promotes carbon cycling through photosynthesis, enhances human care and interaction with microorganisms through material properties, promoting eco-friendly lifestyles [169, 170]. Natto cells were also applied to develop a sustainable biofilm for creating interactive interfaces that can deform with environmental changes, promoting interdisciplinary research in eco-friendly design and HCI [164].
- **`Waste-based Material`**: is obtained from waste and is primarily defined by their utilization of waste as a resource. Usually, it is derived from agricultural by-products, food waste, and industrial waste [120]. There are 7 materials (14.3%) considered waste-based materials. For example, spent coffee grounds can be made as a sustainable 3D printing material for eco-friendly products such as disposable coffee cups and flower pots due to their biodegradable properties [131]. ReClaym is a biodegradable clay made from composted food waste with customized color, texture, and sensing capabilities for handcrafting a diverse range of eco-friendly crafts [18].
- **`Other Material`**: 12 materials (24.5%) are not included in the aforementioned categories, for they do not have the characteristics related to those four classifications. They have a wide range of applications, such as activated carbon being used to develop Vim, a decomposable electrical energy storage solution [141].

4.2.2 Layer 2: Fabrication Method.

Within the second layer, we categorized the fabrication methods that were applied in the included 45 cases into: (1) conventional fabrication, (2) digital fabrication, (3) bio-fabrication, and (4) hybrid fabrication.

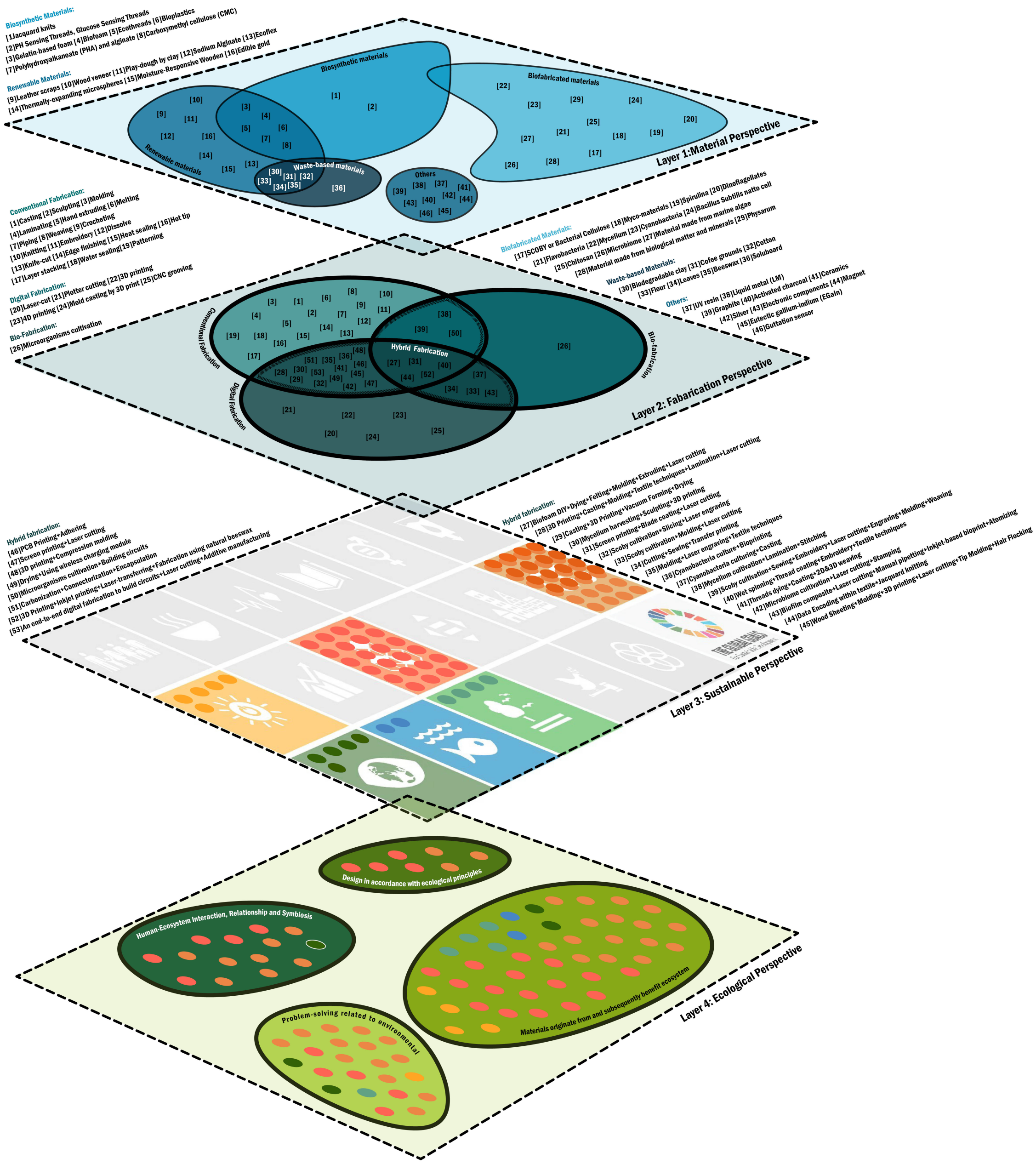

Fig. 5. Taxonomy of Materials Design and Fabrication with Environmental Sustainability Considerations. (1) Layer 1: categorization of materials; (2) Layer 2: categorization of fabrication methods; (3) Layer 3: problem-solving mapped to the SDGs from sustainable perspective; and (4) Layer 4: viewing problem-solving from an ecological perspective as a sustainable transition from SHCI to EHCI.

- **`Conventional Fabrication`**: commonly denotes conventional techniques such as manual methods employed to fabricate prototypes. 19 studies (35.8%) used conventional fabrication. Typical techniques include moulding techniques such as casting [19, 58, 169], moulding [58], and machining [58, 141]. Additionally, it also encompasses weaving [19, 62, 86, 171, 172], crocheting [86], knitting [19, 86], embroidery [88, 172], and cutting [15, 82] used in the fabrication of smart textiles.
- **`Digital Fabrication`**: refers to the manufacturing process that seamlessly converts design and engineering data into digital code that instructs manufacturing equipment to perform rapid prototyping [1]. It was used in 6 studies (11.3%). The widely used technique is 3D printing, consisting of Fused Deposition Modeling (FDM) [95, 140], Stereolithography (SLA) [140], and Selective Laser Sintering (SLS) [140]. Other technologies include CNC machining [11], laser cutting [16, 19, 112, 124, 141, 172], and engraving [111, 112].
- **`Bio-Fabrication`**: refers to the automated creation of structurally ordered physiologically active products from living cells, bioactive compounds, biomaterials, and cell aggregates by bioprinting or bioassembly, followed by tissue maturation procedures [145]. Only 1 article (1.9%) used it. There are instances of cultivating microorganisms, particularly the growth of scoby [16, 19, 111, 112], flavobacteria [61, 130], and mycelium [141, 154, 159].
- **`Hybrid Fabrication`**: integrates various fabrication techniques mentioned in the above classifications into one fabrication process [84]. 27 studies (50.9%) used hybrid fabrication. For example, the e-seed is fabricated utilizing a combination of 3D-printing and laser-cutting [97], and the Scoby is fabricated through cultivation, layering, drying, sewing, embroidering, laser cutting, engraving, moulding, and weaving [19].

4.2.3 *Layer 3: Problem-solving Mapped to the SDGs from a Sustainable Perspective.*

To establish this layer, we map the problems solved in the included 45 studies to the SDGs to analyze how these cases solve problems related to sustainability. It should be emphasized that some cases may solve more than one goal.

- **`SDG 7 (Affordable and Clean Energy)`**: 5 cases (6.0%) can resolve the issues related to this goal. For example, Myco-materials used by Gough et al. [58] are based on fungi and are renewable. By using sustainable 3D printing and manufacturing techniques, they can aid in lowering the amount of non-renewable energy used in conventional manufacturing processes and encourage the development of clean energy technologies. Bell et al. [15] used alganyl, which is made from marine algae and is a sustainable, customizable bio-based material for replacing traditional plastics to support clean energy and environmental sustainability. A durable, adaptable, and degradable electrical energy storage system that may promote clean energy technologies and lessen technological waste was created by Song et al. [141] utilizing activated charcoal as the electrode material. They encourage environmental sustainability and support SDG 7 by offering recyclable and biodegradable substitute materials and lowering dependency on conventional plastics.
- **`SDG 9 (Industry, Innovation and Infrastructure)`**: 24 cases (28.6%) target this issue. Nicolae et al. [110], Koelle et al. [82], Vasquez et al. [154], and Mihaleva et al. [107] studied bioplastics. Issues addressed by this material include creating sustainable materials, reducing electronic waste, increasing material versatility, enhancing environmental awareness and design, supporting the circular economy, and advancing environmentally friendly manufacturing and design technologies, while promoting sustainable development and innovation in the industrial sector. Chitosan, a biodegradable humidity-responsive material studied by Den Teuling et al. [40], provides an environmentally friendly interactive method that does not require external energy, which can help develop novel soft robots, wearable devices, and tactile feedback systems.

- **`SDG 12 (Responsible Consumption and Production)`**: This goal could be accomplished in 40 cases (47.6%). For instance, Lazaro Vasquez et al. [86] addressed the challenges of creating fashion wearables that are sustainable and biodegradable, and encouraged ecologically beneficial design and production methods using gelatin-based foam. Nicolae et al. [110] and Mihaleva et al. [107] adopted alginate as a biodegradable sustainable material, promoting environmentally friendly product design and enhancing users' environmental awareness. Through SCOBY, Bell et al. [19], Ofer et al. [112], Bell et al. [16] and Nicolae et al. [111] proposed innovative solutions to challenges including developing sustainable interactive products, reducing e-waste, utilizing biomaterials to create eco-friendly wearables, and emphasizing a deep understanding of and care for biomaterials through design practices to promote responsible consumption and production patterns.
- **`SDG 13 (Climate Action)`**: 4 cases (4.8%) can achieve this goal. For example, Arredondo et al. [11] have used ceramics to develop the "Blue Ceramics" ecological intervention module system, using digitally manufactured deformable ceramic materials to restore seagrass meadows and improve carbon storage capacity, addressing the problem of climate change and providing innovative solutions for SDG 13.
- **`SDG 14 (Life below Water)`**: 2 cases aim to achieve this goal (2.4%). For instance, Rae-Grant et al. [124] have suggested a sustainable solution for SDG 14 by using moisture-responsive wooden actuators. This approach makes use of wood's moisture-responsive qualities to monitor and safeguard aquatic ecosystems, such as by keeping an eye on changes in pond levels and supporting the conservation and sustainable management of water resources.
- **`SDG 15 (Life on Land)`**: 5 cases (6.0%). The E-seed platform studied by Luo et al. [97] employs wood veneer materials and, through self-drilling deployment, addresses the problems of energy efficiency, environmental impact, and remote monitoring of large-scale sensors and interactive devices in precision agriculture and environmental monitoring. In order to accomplish SDG 15, it also encourages human-nature connection and the use of sustainable materials in associated technologies.

4.2.4 Layer 4: Viewing Problem-solving from an Ecological Perspective as a Sustainable Transition.

As emphasized in the previous sections, we aim to analyze how these studies conducted under the scope of SHCI can provide references for the future development of EHCI. Therefore, in Layer 4, we redefine problem-solving from ecological perspectives while mapping the corresponding SDGs in Layer 3 to show its transition from sustainable perspectives to ecological purposes. Through analyzing the included studies from EHCI perspective, we propose four major topics related to the ecological perspective.

- **`Problem-solving Related to Environmental Sustainability and Ecosystem`**: refers to the cases that aim to solve real problems related to environmental sustainability and the ecosystem (22.6%), such as harvesting renewable energy [96] and reducing waste and material consumption [88]. In an analysis of how each of the SDGs (sustainable perspective, SHCI) is related to the ecological perspective (EHCI), SDG 7, 9, 12, 13 and 15 account for 5.3%, 26.3%, 68.4%, 10.5%, and 5.3% respectively.
- **`Materials Originate from and Subsequently Benefit Ecosystem`**: refers to selecting materials from nature for design and fabrication and ultimately returning to nature or benefiting ecosystem (52.4%). For example, ExCell, made from expanding cellulose (material from nature), can provide a biodegradable solution for creating oxygen in overgrown ponds (benefits the ecosystem) [124]. E-seed, made from wood (material from nature) and inspired by erodium in its design process, provides a biodegradable shape-changing interface for

self-drilling in the soil (benefits the ecosystem) [97, 98]. In this category, SDG 7, 9, 12, 13, 14, and 15 account for 9.1%, 36.4%, 36.4%, 4.5%, 4.5%, and 9.1% respectively.

- **Human-Ecosystem Interaction, Relationship and Symbiosis**: refers to the interaction and coexistence of humans with materials from the ecosystem (eg. bacteria)(16.7%). Most cases used bacteria as raw materials to study how to use them for interface design [20] and explore how humans and ecosystems interact and coexist, such as living with cyanobacteria to care for microbes in everyday life [169]. In this type, SDG 9, 12, 13 account for 35.7%, 57.1%, and 7.1% respectively.
- **Design in Accordance with Ecological Principles**: refers to design based on/following ecological principles (8.3%), such as using flavobacteria's living aesthetics for designing living color interfaces [61] and chitosan's natural actuation properties for eco-friendly interaction design [40]. For designing with ecological principles, SDG 9 accounts for 57.1%, while SDG 12 accounts for 42.9%.

5 FROM LITERATURE REVIEW TO CONFERENCE RETROSPECTIVE: SYNTHESIZING THE KEY DISCUSSIONS FROM THE SPECIAL INTEREST GROUP OF ECOLOGICAL HCI AT CHI 2024

The EHCI SIG meeting at CHI 2024 was organized by a group of HCI researchers who share an interest in materials design and fabrication. The workshop was available to participants that were physically present, as well as remote attendees. 34 participants joined offline and were divided into three groups. Most of them are HCI researchers in the materials design and fabrication field. After an opening discussion, the SIG kicked off with three talks on themes around (1) sustainable interactive devices, (2) sustainable computing, and (3) ecological design for future sustainable products and the environment. Then, a 35-minute deep discussion on personal opinions towards EHCI was held in breakout groups with the participants. During the discussion, each group had a host who invited each participant to share opinions in turn and recorded the whole discussion process.

The key insights obtained from the discussion session [85] that are relevant to materials design and fabrication are as follows:

- **Interdisciplinary Collaborations and Multi-Stakeholders Involvement**: the importance of including sustainability experts from outside HCI in discussions was emphasized, for interdisciplinary collaborations can help bring new insights and more effective strategies to this field. Meanwhile, multi-stakeholders such as indigenous communities have long developed frameworks that integrate humanity, ecosystems, technology, and spiritual stewardship, emphasizing long-term thinking. Indigenous scholars have been publishing works on integrating, combining, or maintaining distinct boundaries between scientific knowledge and traditional or indigenous knowledge and technology. However, the rise of interest has also led to non-indigenous scientists attempting to capitalize on indigenous work rather than collaborating respectfully. This call was made to ensure that ideas related to EHCI do not cause further harm and to include indigenous perspectives genuinely and thoughtfully in the future.
- **Sustainability Considerations in Design and Fabrication Process**: there is a growing trend for designers to incorporate sustainability considerations early in the design process. This proactive approach is seen as crucial for reducing environmental impact. Participants also highlighted the significance of proposing comprehensive sustainability frameworks and current cases of using existing design frameworks (e.g., material-driven design) to guide practices. There was also discussion of evaluating environmental impact, having a better understanding of the sustainability outcomes targeted by a particular technology choice (e.g., optimizing

for carbon versus reducing e-waste), and a need for tools to help integrate these metrics into the design process [167]. As for the fabrication process, the need to reduce waste generated by rapid prototyping was emphasized. Meanwhile, discussions included making the "unmaking" process for low-time commitment fabrications easier, and ideas such as 3D "take-aparter" and water-soluble or coffee-based material printing were proposed. This led to a broader conversation on balancing massive production with household/personal fabrication to achieve more sustainable practices.

- **`Development of New Materials and Technologies`**: the discussions also included potential future directions for research and practice, such as leveraging new materials (e.g., using fully degradable materials as transformers) and technologies.
- **`Reusability, Recycling & Sustainable Lifecycle`**: given the challenges in degrading materials like electronic components and mixed-fabric textiles, the emphasis was placed on reusing and recycling materials to ensure the sustainability of the lifecycle. Meanwhile, using materials from waste in HCI practices was also mentioned.
- **`Challenges of Conducting Testings`**: two types of testing were mentioned: user study and environmental testing. Firstly, discussions on the user studies emphasized the necessity of addressing how user studies should be conducted within the context of EHCI and identified three main types of users: researchers, designers, and end-users. Secondly, a significant challenge noted was the difficulty in scaling lab test results, such as biodegradability tests, to real-world settings across different regions. For example, biomaterials may behave differently in various environments (e.g., South America, China), which highlighted the need for more localized insights in conducting testings.

6 REFLECTIONS ON APPROACHES OF MATERIALS DESIGN AND FABRICATION: TOWARDS FUTURE DESIGN CONSIDERATIONS

In this section, we first deeply analyze the included studies from a systems perspectives. Then the current theoretical approaches of materials design and fabrication in the HCI and design fields are compared to explore the space of advancing the approaches to better facilitate the future development of EHCI. Finally, we propose a framework of materials design and fabrication for future EHCI practices.

6.1 Analysis of Existing Studies of Materials Design and Fabrication for Sustainability in HCI from a System Perspective

To understand the 45 studies included more comprehensively, we analyzed and classified them into three categories from a systems perspective (Fig.6): (1) electrical, (2) mechanical, and (3) biological systems. We define these three categories of systems according to the following criteria and self-defined scope:

- **`Electrical Systems`**: refers to the prototype that consists of complex electrical components (e.g., PCB) to compute, control and power. 15 studies are regarded from an electrical systems perspective.
- **`Mechanical Systems`**: encompasses the physical prototypes which achieve interactive functions (e.g., shape-changing) through its mechanical structure, properties of being able to be powered by external stimuli (e.g., moisture) etc., rather than depending on electrical components. 20 studies are divided into mechanical systems.

- **`Biological Systems`**: integrates the living artefacts (e.g., organisms, cells, biological molecules) in designing interactions through a bio-hybrid approach. 13 studies are viewed from a biological systems perspective, for they introduce cells [164] and bacteria [61, 130, 169] etc. into interaction design.

Based on the aforementioned three kinds of systems, we compared and analyzed the included studies from a system perspective through the taxonomy illustrated in Fig. 6. We aim to find and reflect on three aspects: (1) what the existing studies have already studied, (2) what their advantages and disadvantages are, and (3) where the future design opportunities lie.

6.1.1 Layer 1: What has already been studied in different systems?

State-of-the-art cases related to electrical systems, mainly focused on e-waste management and were conducted with a focus on: (1) reusing the recycled electronic components/waste to prototype devices [35, 90, 154, 163, 168]; (2) applying renewable or degradable materials to the electronic components to reduce waste [12, 36, 91, 97, 139, 141, 160, 168, 172]. We also found some preliminary attempts in (1) developing battery-free [7, 141], zero-energy ubiquitous systems [5], and (2) integrating with mechanical [96, 97, 159] and biological [91, 154] systems.

For the mechanical systems, researchers have studied: (1) developing and applying sustainable materials into the design and fabrication of a physical prototype [27, 82, 86, 87, 107, 124, 140, 168] and (2) exploring shape-changing/morphing mechanisms and principles based on material properties, mechanical structure, etc. [11, 40, 95–97, 124].

The included studies related to biological systems show research trends in exploring how living artefacts can coexist with humans through designing (1) direct interactions [130], (2) care practices [169, 170], and (3) unique user experiences [61, 112], while also (4) leveraging their biological affordances to create shape-changing interfaces [164] and other prototypes [20, 58, 62, 91, 111, 154].

6.1.2 Layer 2: What are the advantages and disadvantages of different systems?

Interactive systems based on electrical approaches can, typically, better implement more robust control, and computation. However, most electrical-based approaches decrease sustainability given their use of metals and high-energy manufacturing processes.

Meanwhile, several existing studies [97, 98] show interactive systems based on mechanical approaches can achieve the expected interactive functions (e.g., shape morphing) through their mechanical structure or by being activated by environmental stimuli, which can operate without the need for additional electronic parts. Since they does not necessarily rely on electricity, such prototypes usually require special considerations and knowledge about the material structures , reducing their accessibility to the broader engineering discipline [95]. The fabrication process can also result in unsustainable consequences, such as waste, overuse of materials and energy consumption [131].

Conversely to both prior approaches, interactive systems based on biological or organic materials pave a new way of interaction by considering non-human living/biological components with more-than-human and ecological perspectives. This can strengthen the relationship between humans and living artefacts, further promoting human-nature symbiosis. However, integrating biological, living components, such as bacteria, in HCI systems requires knowledge about potential risks [13] (e.g. bio-safety [4, 108, 134]), ethical concerns (e.g. intervening in the living conditions of living artefacts through artificial means (human-centric purposes) to achieve the expected interactive effects) [68], emergence and unpredictability [60], economic justice issues (e.g. the economic impacts of biotechnological solutions for all stakeholders involved [13]), and potentially conflicting values of the various human, non-human and technological agents involved in multispecies interactions [60]. The aforementioned factors must be considered seriously in the design process [60].

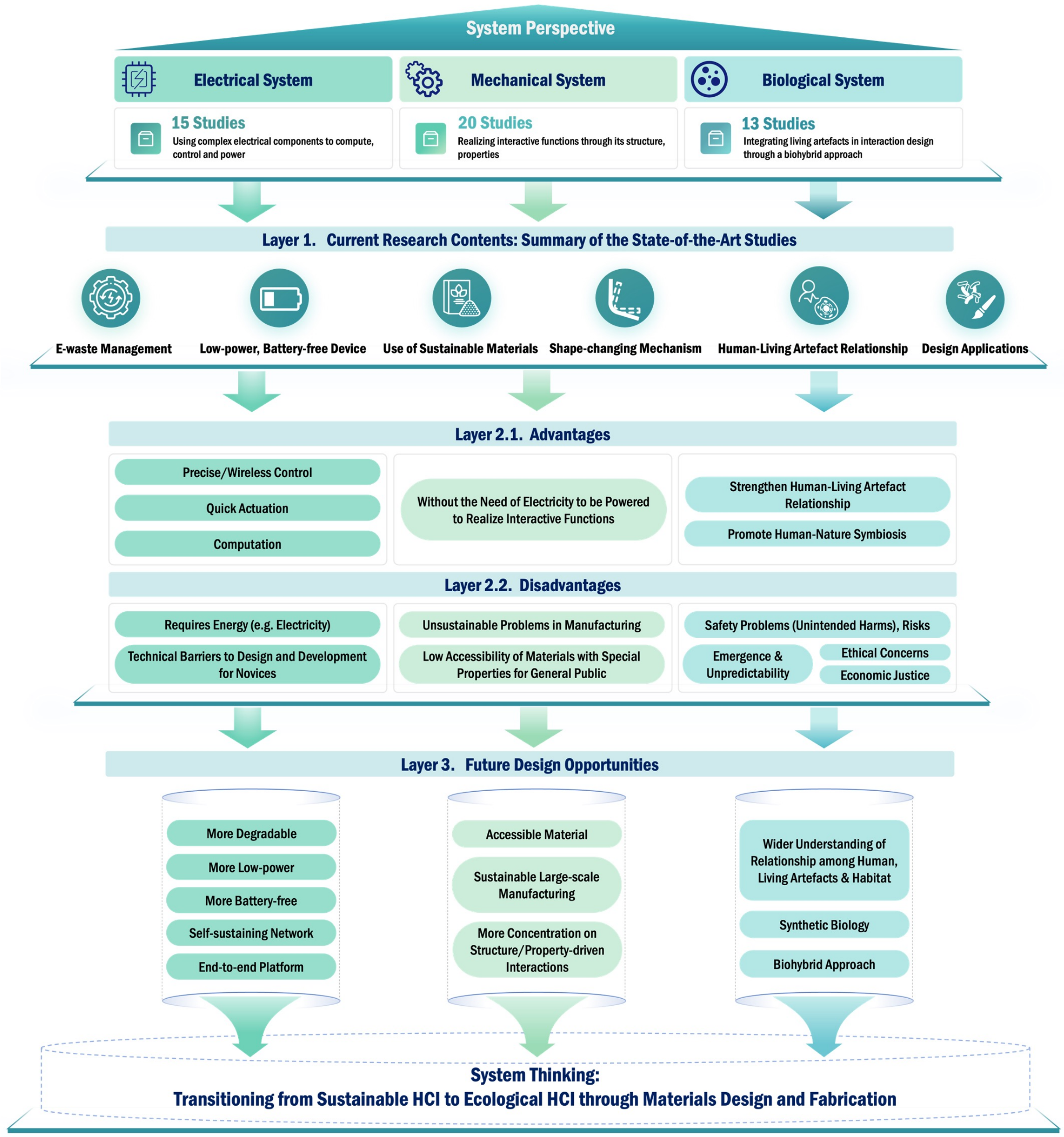

Fig. 6. Analysis of the included studies from a system perspective. Three systems are classified by the authors: electrical, mechanical, and biological systems. The figure consists of three layers. (1) Layer 1: summary of what has already been studied in different systems; (2) Layer 2: the advantages and disadvantages of each system; and (3) Layer 3: envisioning future design opportunities of different systems.

6.1.3 Layer 3: What are the future design opportunities of different systems?

- **`Electrical System as a Platform for Sustainable Computing`**:

(1) Towards a More Self-sustaining Network of Degradable, Low-power, Battery-free System: Arora et al. [5–10], Waghmare et al. [158], Zhang et al. [166], Teng et al. [148] and Yen et al. [165] have already conducted related studies in fabricating self-sustaining, self/low-power, battery-free ubiquitous devices with electronics. The aforementioned state-of-the-art cases show preliminary attempts in designing these sustainable electrical systems. Future practices should deeply consider advancing the technology and broadening their potential applications in ecosystems and in environmental sustainability scenarios.

(2) Developing an End-to-end Design Platform for All: the development of electrical systems, especially the identification, selection, use and circuit design of electronic components, is still difficult and challenging for novice stakeholders in this field. Researchers have started to discuss the future potential of developing an end-to-end design platform. For example, Yan et al. [163] discuss a more advanced, end-to-end software pipeline that can optimize housing generation and reduce design effort for designers. Cheng et al. [35] recognized the necessity of broadening the impact and design space to allow a wider spectrum of designers to use electronics. These considerations motivate researchers to develop end-to-end, user-friendly design platforms for all potential practitioners regardless of background.

- **`Mechanical Systems as Actuators for Interactive Dynamics`**:

  (1) Applying More Accessible Materials in Design & Fabrication: Lu et al. [95] reflected that many of the responsive materials used in their design cases are both costly and challenging to produce, often requiring specialized laboratory procedures, conditions, and equipment. This drawback limits their widespread adoption and applicability. Future research needs to focus more on how to design with common materials, or develop tools to provide designers with more convenient hands-on experience and accessible guidelines or material libraries [95].

  (2) Adopting a More Sustainable Large-scale Manufacturing Approach: Rivera et al. [131] recognized that the widespread adoption of 3D printers exacerbates existing environmental challenges as these machines increase energy consumption, and increase plastic usage and output waste. Therefore, choosing appropriate materials for 3D printing is tightly connected to these challenges, and as such researchers and designers are exploring sustainable alternatives to plastics. Deshpande et al. [41] adopted a life-cycle mindset to discuss the sharping interests in the sustainability of Fused Deposition Modeling (FDM). These considerations motivate us to develop or adopt a new way of manufacturing in the future, especially for making physical mechanical prototypes.

  (3) Learning from the Wisdom of Structure & Properties to Design Interactions: relevant cases in [11, 40, 95–97, 124] reveal a research path of learning from the beauty, mechanism, and wisdom of specific mechanical structures and material properties to design shape-changing interfaces. These practices are often related to bio-inspired/biomimetic design, which showcases the real beauty and wisdom of mechanical systems. Future designs could pay more attention to learning these principles and applying them in interaction design.

- **`Biological Systems as Incubators for Regenerative Ecologies`**:

  Our previous analysis demonstrates that biological systems can facilitate interactions beyond the boundaries of a single artefact, enabling dynamic exchanges among humans, living artefacts, their shared habitats, and even broader ecosystems. Through these interactions, new opportunities emerge for advancing regenerative ecologies [75] — systems characterized by mutualism, creativity, and co-evolution. Future practices could explore the following directions to expand on this potential:

(1) Expanding the Understanding of Interactions among Humans, Living Artefacts, and their Shared Habitat: In 1992, Edward Wilson anticipated that the 21st century would be characterized as an era of ecological restoration of ecosystems [161]. However, efforts to date have been severely limited by a clear lack of recognition that our anthropocentric perspective is only one of many ecologies of the world [31, 45, 49]. From these discussions has emerged a systemic vision of ecology that embraces the concept of restoration as a pursuit of sustainability, one that goes beyond equilibrium thinking to include a deeper understanding of the co-evolution of humans and the ecosystems they inhabit, recognizing their inextricable interdependence [75]. Risseeuw et al. [130] urged that a more comprehensive understanding of the interdependencies among habitat, microorganisms, and interaction variables in real-world settings is required for future practices.

(2) Advancing "Living Machines" in HCI through Synthetic Biology and Biohybrid Approaches: Among the included studies, several illustrate canonical examples in which non-human organisms are leverages as intrinsic components in the functioning of an interactive system. For instance, Lu et al. [91] includes a living slime mold as an electrical wire and sensor in an interactive smartwatch; here, all aspects of the living organism are intrinsic parts of the user's interactions, even caring for the health of the organism. Also from a functional perspective, Yao et al. [164] incorporated natto cells as nano-actuators for designing transformable thin sheet materials that respond to humidity change, through which they reflected that relevant technologies in synthetic biology that focus on engineering the DNA structure could be applied to creating richer characteristics of the material. Groutars and Risseeuw et al. [61] explored the aesthetics of flavobacteria, favoring the organism's own agency over the ability to control its behavior, yet recognizing the possibility of learning from synthetic biology and materials science, to develop engineered living materials. Both aforementioned studies have demonstrated the reflective considerations and ethical concerns of exploring the possibilities of leveraging engineering technologies in designing interactions with biological/living systems.

Herein, we refer to the concept of "living machine", initially proposed in the field of robotics [23, 66], which aims to harness the versatility and sustainability of living organisms through biomimetic or biohybrid approach [122]. By exploiting those natural principles, scientists hope to render a renewable, adaptable, and robust class of technology that can facilitate self-repairing, social, and moral– even conscious -machines [121]. Existing studies in natural science and engineering field have shown the integration of cell (e.g., bacteria, algae), tissue at different scales into machines for various functions (e.g., actuation, control, sensing) [144]. The biological components and biologically synthetic materials in these "living machines" can be combined with multiple technologies (e.g., microfluidics) to develop biohybrid robotics [144].

In the context of HCI, researchers have also had discussions relevant to "living machine". For example, Pataranutaporn et al. [116] systematically analyzed the opportunities and challenges for integrating living microorganisms in HCI, while also highlighting the necessity of integrative interfaces between people, computers and biological materials [115]. Although emerging HCI studies have begun to concentrate on designing interactions based on certain properties of the living/biological organisms/materials, future studies should be conducted to demonstrate the "intelligence" of the biological system in HCI, gaining inspirations from the current studies of biohybrid robotics [54]. Not only can it promote the integration and symbiosis of human and biological system, but also realize more versatile functions of interaction, self-repair, actuation, locomotion or perception at the intersection of synthetic biology, HCI and design [60]. Thus, biological systems will have the potential to truly disrupt the traditional paradigm of HCI “without the explicit requirement of a traditional computer” in an automatic and smart way [113].

6.2 Comparison of Current Theoretical Approaches of Materials Design and Fabrication in HCI & Design

Fig. 7 introduces and compares current theoretical approaches of materials design and fabrication introduced by HCI or design researchers. Firstly, both material-driven design (MDD) and materials experience for HCI guide material design practices from a macro perspective, rather than limiting the approaches to a specific type of material. However, material-driven textile design (MDTD) and the design pipeline for sustainable morphing matter only focus on specific materials such as textile and morphing matter respectively. Thirdly, as materials design and fabrication is an interdisciplinary practice [3, 29, 46], we also analyze whether the design approach highlights the role of stakeholders. Karana et al. [73], Giaccardi and Karana [56] involved designers and users, Ribul et al. [128] involved designers, material scientists and other participants in the design process. However, Patel et al. [117] did not consider multi-stakeholders engagement. Finally, as for sustainability considerations, Karana et al. [73] reported using MDD to design for sustainability, while Patel et al. [117] emphasized sustainability during whole lifecycle, including the fabrication and recycling processes.

Reference	Name of the Approach	Publication Venue	Material that Suits the Approach	Stakeholders Involved in the Design Process	Sustainability Considerations
Karana et al., 2015	Material Driven Design (MDD):Design for Materials Experience	International Journal of Design	Not limited	Designers, users	Yes (Design for sustainability)
Giaccardi and Karana, 2015	Foundations of Materials Experience: An Approach for HCI	ACM CHI 2015 Conference	Not limited	Designers, users	Not mentioned
Ribul et al., 2021	Material-Driven Textile Design (MDTD): A Methodology for Designing Circular Material-Driven Fabrication and Finishing Processes in the Materials Science Laboratory	Sustainability	Textile	Designers, material scientists, participants	Not mentioned
Patel et al., 2023	Design Pipeline for Sustainable Morphing Matter	Advanced Materials Technologies	Morphing matter	Not mentioned	Yes (Sustainability in manufacturing, transportation, use and end-of-life)

Fig. 7. Comparison of current theoretical approaches of materials design and fabrication. We compare the approaches from four aspects: (1) publication venue, (2) material that suits the approach, (3) stakeholders involved in the design process, and (4) sustainability considerations in the framework.

6.3 Design Framework of Materials Design and Fabrication for Future EHCI Practices

Based on the aforementioned analysis and discussions during the SIG at CHI 2024, we propose a design framework to guide future materials design and fabrication practices in EHCI. This framework consists of four design phases: (1) design briefing, (2) design action, (3) design evaluation, and (4) design iteration (Fig. 8).

6.3.1 Phase 1: Design Briefing.

Phase 1 aims to put forward the design brief. The input information is design scenarios and needs. As discussed at the CHI 2024 SIG, it is important to involve multi-stakeholders in EHCI practices through interacting with them using design research methods such as interviews, focus groups, and participatory design workshops. This allows us to better understand what the problems are and identify the fundamental knowledge related to ecosystems, thus obtaining design objectives and directions. Specifically, we list potential stakeholders (partners) who serve different roles to contribute to the design process: designer, material scientist, environmental scientist, manufacturer & supplier, eco advocate & NGOs, government & eco-regulator, engineer, indigenous community and user.

6.3.2 Phase 2: Design Action.

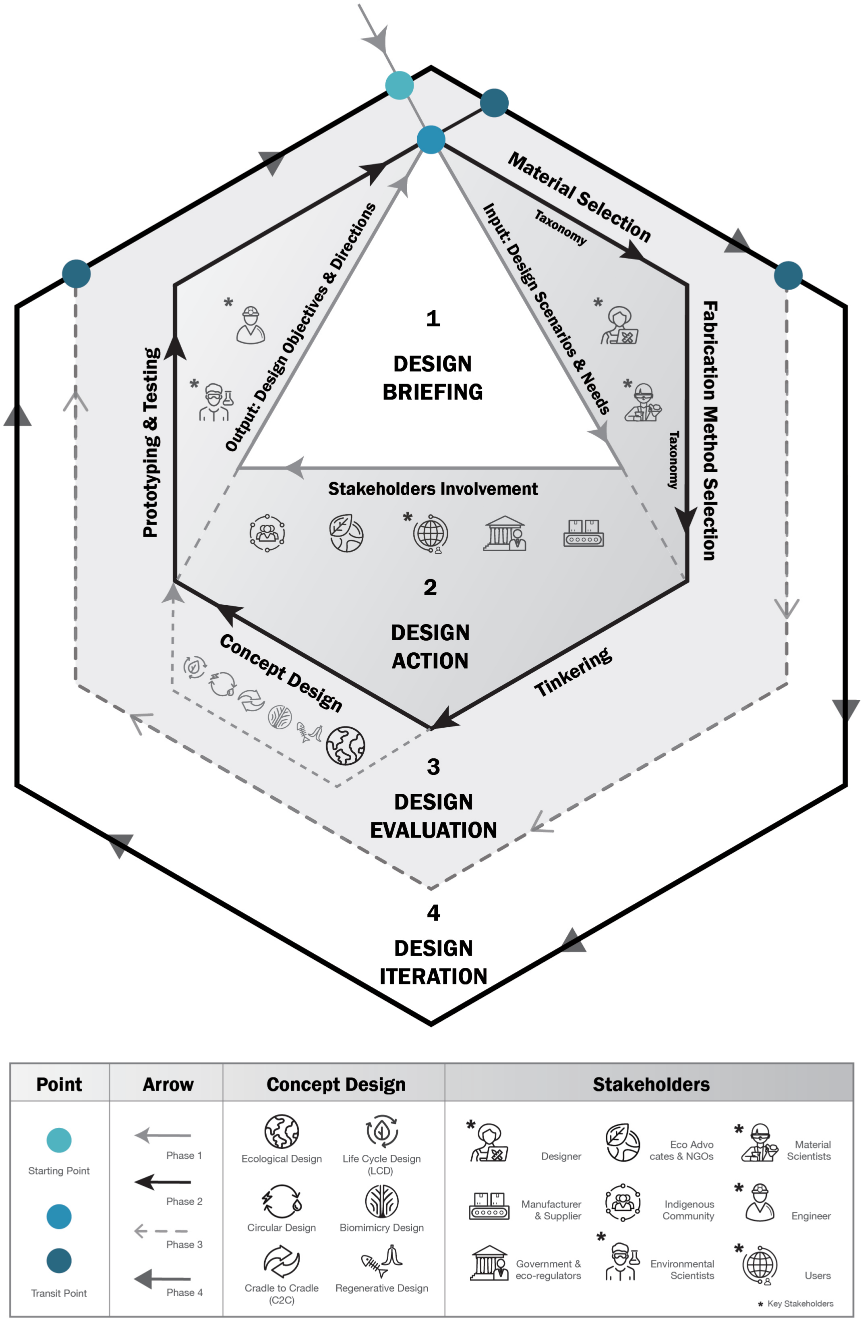

Fig. 8. Design framework of materials design and fabrication for future practices in EHCI: (1) Phase 1: design briefing, (2) Phase 2: design action, (3) Phase 3: design evaluation, and (4) Phase 4: design iteration.

Phase 2 focuses on taking action on the design and prototyping following the design brief, which contains five steps:

- **Step 1: Material Selection**: according to Karana et al., the material selection process can be defined as the systematic examination and measurement of the structure, characteristics, and behavior of a material in order to make predictions about its performance in particular circumstances. The careful use of materials in contemporary design not only improves the functioning and sustainability of a product, but also fosters a distinctive product image and enriches the user experience [76]. Effective material selection necessitates a strong partnership between designers and material scientists to ascertain adherence to ecological principles such as biodegradability, renewability, and recyclability. Jahan et al. propose that screening and rating are two crucial stages in the process of material selection [71]. Lu et al. [95] discussed future research directions to develop and expanding on a material library, which would increase the variety of available materials and assist in material selection. The taxonomy shown in Fig. 5 can serve as a valuable resource for guiding the choice of materials, therefore assuring that decisions are grounded in environmental sustainability and customized to meet particular design objectives.
- **Step 2: Fabrication Method Selection**: refers to the process of choosing a suitable fabrication method that meets the design requirements. Lu et al. [93] conducted a comparison of various potential fabrication methods in order to select the most suitable one for multilayer heat sealing. To select the fabrication method, the second layer of the taxonomy presented in Fig. 5 can be used as a tool to integrate knowledge and make fabrication decisions among diverse expertise. Specifically, in order to ensure sustainability related EHCI considerations in the fabrication process, we suggest choosing a method that can reduce waste and save energy [96, 131], while simultaneously increasing the productivity.
- **Step 3: Tinkering**: the concept of "tinkering" in the design field first refers to the process of experimenting with materials to learn, understand, and evaluate the technical properties and experiential qualities of materials to assist in the design practice [114]. In this framework, we extend this concept to "tinkering with materials and also with fabrication methods", in order to have a hands-on experience on how materials and engineering techniques can contribute to the development of interactive technologies.
- **Step 4: Concept Design**: refers to the stage of developing ideas and design solutions. Drawing upon the six SDGs outlined in Layer 3, as well as the ecological perspectives in Layer 4, both in Fig. 5, we suggest approaching concept design from three perspectives: addressing materials and fabrication selection, sustainability perspectives, and ecological perspectives, which can help facilitate the transformation from SHCI to EHCI.
  By incorporating these perspectives, designers can bridge the gap between material and fabrication choices and ecological sustainability, as discussed in Subsection 2.2. Therefore, after material and fabrication method selection and tinkering, designers need to develop a concept design based on the design needs and objectives summarized in Phase 1. In addition to traditional design tools and techniques like brainstorming and mood boarding, we suggest environmental sustainability/ecology-specific design strategies to be considered in designing for EHCI purposes: Life Cycle Design (LCD), Circular Design, Cradle to Cradle (C2C), Biomimetic Design, Regenerative Design, and Ecodesign. Each of these strategies provides a rigorous, evidence-based strategy to addressing key challenges identified earlier, such as minimizing waste, enhancing resource efficiency, and utilizing materials in a manner that is not only sustainable but also contributes positively to the ecosystem. By applying these strategies, designers can ensure that their work supports both the SDGs and the ecological perspective emphasized in the

EHCI, which is in line with the sustainable and ecological perspectives we mentioned in the last two layers of the proposed taxonomy (Fig. 5).

(1) Life Cycle Design (LCD): prioritises the thorough evaluation (eg., life cycle assessment) of environmental aspects during the product development phase and integrates them into the design to reduce environmental effects over the whole lifespan of the product. This approach ultimately results in the development of more sustainable production and consumption methods [155, 156]. Zhang et al. [167] developed DeltaLCA, an open-source interactive design tool that addresses the dual challenges of automating life cycle inventory generation and data availability by performing comparative analyses of electronics designs. HCI researchers and designers with an LCD mindset in this field should consider how to design to serve the entire life cycle from a macro perspective (eg., designing and fabricating with materials that have the lowest environmental impact[155]) at the beginning of the concept design phase, corresponding to Layer 3 of Fig. 5, especially SDG 12 (Responsible Consumption and Production) and SDG 9 (Industry, Innovation and Infrastructure).

(2) Circular Design: promotes the development of systems and products that foster restoration and regeneration, eradicating the notion of waste by incorporating waste produced by one natural process as an input to another [99]. This strategy inspires us to incorporate principles of durability, adaptability, and diverse recycling methods such as reusing, refurbishing, remanufacturing, and recycling. We must consider establishing closed-loop systems that minimize resource consumption and environmental impact to facilitate designing for a circular economy [33].

(3) Cradle to Cradle (C2C): is the deliberate design of products to facilitate the recycling of materials in a closed-loop system, thus guaranteeing their indefinite reuse without any degradation. It challenges the conventional "cradle to grave" methodology, which involves disposing of products when they reach the end of their useful lifespan [14]. Following this approach, we should proactively learn from nature, recognizing the materials as nutrients that can be returned to nature. During the concept design process, we must envision the end-of-life of interactive interfaces, ensuring a continuous circulation of materials.

(4) Biomimicry Design: aims to draw inspiration from natural processes, structures, and ecosystems to address human design problems in a manner that is environmentally sustainable [77]. For example, we can draw inspiration from the material properties of biological organisms, such as their strength, resilience, and self-healing capabilities, to fabricate high-performance biomimetic prototypes.

(5) Regenerative Design: also known as "regenerative design and development", embraces an ecological worldview where Earth is acknowledged as a complex, adaptive, and dynamic living system [151], while the ethos of regenerative design and development is to restore and foster new relationships between humans and natural systems so that all life might co-evolve and thrive [67, 75, 125]. The key to regenerative design and development as a practitioner is a shift in mindset from a mechanistic worldview to an ecological worldview, moving from reductionist assumptions to systems thinking [30, 39, 101, 125]. This requires designers and HCI practitioners to become familiar with ecological knowledge and systems thinking to integrate the principles of living systems into our practice [100, 101].

(6) Ecological Design (Ecodesign): is a more macro design concept, which integrates the above design methods to guide designers to design for the ecosystem, and was mentioned by the participants at CHI 2024 to be suitable for guiding EHCI practices. Ryn and Cowan [153] defined it as "any form of design that minimizes environmentally destructive impacts by integrating itself with living processes". Eco-design, which mimics natural life cycles, can be used to achieve a truly circular economy. An eco-design product may have a cradle-to-cradle life cycle, resulting in zero waste throughout the entire process.

Besides considering relevant design methodologies, we should also pay special attention to: (1) the engineering and technical solutions to develop prototypes, (2) which system (e.g., electrical, mechanical, biological system) mentioned in the former subsection can the target design solution be included in.

The concept design encompasses this obligation by taking into account not only the functionality of the product, but also its interaction with and contribution to natural ecosystems. Addressing the transition from SHCI to EHCI as outlined in Subsection 2.2, a heightened emphasis is placed on a more profound ecological accountability.

- **`Step 5: Prototyping & Testing`**: refers to using the fabrication method selected in Step 2 to make a prototype, then conducting preliminary testing of that prototype, such as fundamental performance and usability. The specific strategy, features, and substance of testing are contingent upon the design scenario and requirements established during the initial phase.

6.3.3 Phase 3: Design Evaluation.

The evaluation in EHCI scenarios is mainly conducted in nature, to assess the effects of the prototype on environmental sustainability. As discussed in the SIG at CHI 2024, evaluation methods and metrics are required to be specified for the future development of EHCI [92]. Therefore, in this study, we will not go into detail about the specific methods of the design evaluation process.

6.3.4 Phase 4: Design Iteration.

Based on the results obtained in Phase 3, it may be necessary to refine and iterate on the prototype in order to consistently evaluate and enhance it, even if this results in deviating from the initial approach of gradually achieving the design criteria that were initially required [37]. At this phase, we may retrace each of the previous steps, which will make this design framework a closed loop to truly reflect the systematic nature of the design.

7 DISCUSSION

7.1 Action for a More Sustainable Tomorrow: Pushing forward Materials Design and Fabrication Practices at the Intersection of SHCI and EHCI

As a concept based on the existing SHCI concept, EHCI cannot exist as an independent field for it is proposed to expand the scope of SHCI to a perspective that takes more consideration of ecosystem sustainability, rather than replace SHCI. Therefore, the 45 included studies in this study are positioned at the intersection of traditional SHCI and EHCI. Through reviewing the 45 included studies, we suggest that HCI researchers consider the following aspects to facilitate current practices and achieve a more sustainable tomorrow.

7.1.1 Co-design with More-than-humans through Human-non-human Collaborations.

As introduced in the Introduction and Related Work sections, SHCI is developed from a human-centered perspective while EHCI focuses more on more-than-human and nature-centered approaches. This shift in perspective is due to the fact that design has contributed to the establishment of anthropocentric perspectives by spreading human-centered production and consumption patterns, which often do not take into account the rights and interests of non-human entities [132], and leading to the current unsustainable changes in our ecosystems [53, 147]. This has forced researchers to recognize that an ontological shift should be achieved, indicated by the human-centered hierarchy being changed through a more inclusive consideration of non-human entities [52]. In this context, cradle-to-cradle design and biomimetic design as mentioned in Fig. 8 emphasize regenerative approaches not only related to human future generations, but also to non-human species [32, 77]. In other words, designers have been taking a post-human perspective, focusing on non-hierarchical interrelationships between humans and non-humans, and this paradigm shift will greatly promote a sustainable transformation [55]. Therefore, the shift in the role of design is recognized on two different levels: (i) the shift towards new sustainable production and consumption patterns, then towards a non-human-centered perspective, and (ii) the interconnectivity between human and non-human entities to achieve a collaborative future [132].

In this context, we should engage interdisciplinary experts and stakeholders in the design process, listening to their suggestions and knowledge from a human-centered perspective of SHCI. We should also place ourselves in the natural environment to conduct field studies to observe, explore, and investigate the needs of the ecosystem, demonstrating the nature-centered features of EHCI. By considering both human and non-human factors, we can balance at the intersection of SHCI and EHCI to better promote emerging studies and shift from the traditional SHCI domain to a broader scope with EHCI features for a sustainable transition. What is more, Romani et al. [132] have made initial explorations in developing co-design tools for human-non-human collaboration, finalizing a tool that can be used to share and expand reflections about futures without hierarchies, that are not human-centered, and that result in sustainable progress and hope, and are participatory. This research progress also inspires us to explore how we can co-design with non-humans in materials design and fabrication practices for EHCI.

7.1.2 Navigate Scale, Growth, and Production Limitations in EHCI Practices.

While this paper focuses more on directions for sustainable materials design and fabrication approaches in HCI, the challenges of scaling these innovations beyond the prototype stage is still there. Khurana et al. [78] discusses the hardware manufacturing challenges, where there exists a significant gap between creating functional prototypes and achieving viable production - particularly for low volumes of hundreds to thousands of units. This is especially relevant for EHCI, where sustainable materials and processes may work well in laboratory settings but face numerous scaling challenges. For instance, while bio-fabricated materials show promise as sustainable alternatives, scaling their production requires careful consideration of manufacturing variability, component tolerances, supply chain reliability, and quality control processes. The push for novel materials and rapid prototyping in HCI research must be balanced against what Khurana et al. [78] identify as critical productization requirements - including design for manufacturing/assembly/test, compliance testing, and proper manufacturing documentation. We suggest that future EHCI research needs to engage more deeply with these manufacturing realities early in the design process, while maintaining commitment to ecological principles. This may mean developing production strategies that can scale appropriately while preserving sustainability benefits, creating comprehensive test specifications and procedures and establishing quality control processes that work with novel sustainable materials.

Meanwhile, as discussed at CHI 2024 and mentioned in previous studies, we suggest that we should not put all effort into solving ecological problems through HCI practices, but also pay special attention to the unsustainable outcomes caused by the choice of material types and fabrication methods. For example, while waste-based materials and bio-fabricated materials present a viable option for sustainable design and manufacturing, large-scale production and usage of these materials may raise environmental concerns [131]. Therefore, to achieve a real sustainable transition, researchers must take into account the environmental effects of the full life cycle and investigate ways to mitigate these effects when designing and producing prototypes. We can also develop new tools for life cycle assessment (e.g., previous study conducted by Zhang et al. [167]), calculate carbon footprints through quantitative methods and compare them with traditional methods to see whether the new methods are more sustainable.

7.1.3 Adopt a Post-Growth Orientation in Designing and Making for Ecological HCI: Reflections from Social-Technical Perspectives.

Unlike other past calls to action in HCI, where a great expansion of research and practice is needed to address a critical need– be it in accessibility, interaction, or fabrication– we must be careful in all of our approaches in not making the problem worse by building yet more devices and scaling up processes that seem slightly better but may yet have unknown negative factors. Many scholars have questioned if scalability and striving for growth is aligned with survival, such as Anna Tsing's work saying "...scalability has left ruins in its wake. Nonscalable effects that once could be swept under the rug have come to haunt us all [152]."

HCI has recently grappled with the concept of "post-growth," which emerged in response to the environmental and social challenges caused by striving for continued economic growth– where a business is only successful if it makes more and more money, versus success defined as it being sustainable and offering a service that is valuable. Post-growth advocates for a shift from a growth-centric model to one that prioritizes sustainability, equity, and well-being, and making design and deployment decisions from that frame. This mindset is crucial for addressing ecological crises (e.g., climate change) and ensuring an equitable and environmentally sustainable future for all [70].

It combines theories and ideas from degrowth and post-development philosophies to achieve a global steady-state economy [142]. This social transition calls for actions to treat technical issues from social-technical perspectives (e.g., economy, social justice, environment etc.). In the field of HCI, Sharma et al. [135] mentioned that the aim of designing interactive technologies to address sustainability [80, 143, 150] is to reduce overproduction and overconsumption of resources and move beyond the growth (dominant) economy that seeks incessant economic growth [89, 129]. At the same time, the advancement of HCI itself relies significantly on continued economic growth [26, 109]—to scale technology, reach new users and geographies, and fit more processing power into smaller hardware. To this end, some HCI researchers have problematized the field's engagement with growth, suggesting the post-growth philosophy as an alternative [135, 136]. Meanwhile, at CHI 2024, a workshop themed around Post-growth HCI was organized to co-envision HCI beyond economic growth [136], inviting HCI professionals to integrate post-growth ideas into transformative HCI practices for technology-mediated social changes.

This paper focuses on materials design and fabrication in HCI towards a new framing of sustainability in HCI that is Ecological and Ecosystem-focused, with a more than human view. This view naturally consists of technical, social, and economic aspects that are highly intertwined and also dynamic. For the technical aspect, engineering approaches are needed to design and fabricate. Social dynamics and constraints inform applications, scalability, and durability of engineering solutions– and highlight both positive and negative impacts engineered systems may have. Economic aspects influence how these systems may be deployed and the realities of fabrication. Therefore, future practices can take a post-growth orientation to continually evaluate Ecological HCI studies, designs, and research at a level of social economy, thus reaching an ecological economy status [142]. We acknowledge that notions of Ecological HCI and post-growth could, at times, be in conflict and, at other times, in harmony. We envision that the study, design, and development of digital post-growth technologies through materials design and fabrication can eventually lead to a more ecological, just, and humane post-growth society.

7.2 Limitations & Future Work of the Study

In this study, the amount of the included articles from top-tier conferences in the HCI field is limited, which also led to the need to include more niche publications relevant to the scope of this study. The design framework proposed in Fig. 8 is a reflection merely based on analyzing the state-of-the-art studies and the insights obtained from the SIG of EHCI at CHI 2024. However, the effectiveness of this framework has not been validated, which motivates us to apply this framework in future research practices to test and improve it. Lastly, this study currently focuses on only one challenge facing EHCI; however, as mentioned in the introduction of the design framework, how to conduct design evaluation in the environment is also of great importance. Therefore, future work should be done to systematically provide guidelines for the future development of EHCI.

8 CONCLUSION

Through reviewing 45 influential human-computer interaction prior works with a focus on environmental sustainability (either through their use of organic or living materials or technical approaches), we firstly summarized state-of-the-art research progress from a quantitative perspectives. Secondly, we proposed a taxonomy to categorize and identify 5 types of materials, 4 categories of fabrication methods, 6 sub-topics of the Sustainable Development Goals solved by the included studies, and 4 major topics during problem-solving related to ecological perspectives. Finally, we reflected on the content of the entire study and the discussions that took place at ACM CHI 2024's workshop on ecological HCI, and put forward a design framework consisting of four major design phases. We intend this literature review to be an exploratory and pathbreaking study in ecological HCI to obtain inspiration from existing literature for the future development of ecological HCI.

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References

[1] Raneem Abdulghany, Mariam Youssry, and Samah Elkhateeb. 2022. Digital fabrication as an approach for innovative architecture education. *MSA Engineering Journal* 1, 4 (2022), 79–97.

[2] Raeid MM Abed, S Dobretsov, and K Sudesh. 2009. Applications of cyanobacteria in biotechnology. *Journal of applied microbiology* 106, 1 (2009), 1–12.

[3] Sean Ahlquist and Achim Menges. 2015. Materiality and computational design: emerging material systems and the role of design computation and digital fabrication. In *The Routledge Companion for Architecture Design and Practice*. Routledge, 149–168.

[4] Mark C Andersen, Heather Adams, Bruce Hope, and Mark Powell. 2004. Risk assessment for invasive species. *Risk Analysis: An International Journal* 24, 4 (2004), 787–793.

[5] Nivedita Arora and Gregory D. Abowd. 2018. ZEUSSS: Zero Energy Ubiquitous Sound Sensing Surface Leveraging Triboelectric Nanogenerator and Analog Backscatter Communication. In *Adjunct Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 81–83. https://doi.org/10.1145/3266037.3266108

[6] Nivedita Arora, Vikram Iyer, Hyunjoo Oh, Gregory D. Abowd, and Josiah D. Hester. 2023. Circularity in Energy Harvesting Computational "Things". In *Proceedings of the 20th ACM Conference on Embedded Networked Sensor Systems* (Boston, Massachusetts) *(SenSys '22)*. Association for

Computing Machinery, New York, NY, USA, 931–933. https://doi.org/10.1145/3560905.3568106

[7] Nivedita Arora, Ali Mirzazadeh, Injoo Moon, Charles Ramey, Yuhui Zhao, Daniela C. Rodriguez, Gregory D. Abowd, and Thad Starner. 2021. MARS: Nano-Power Battery-free Wireless Interfaces for Touch, Swipe and Speech Input. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 1305–1325. https://doi.org/10.1145/3472749.3474823

[8] Nivedita Arora, Thad Starner, and Gregory D Abowd. 2020. SATURN: An introduction to the Internet of Materials. *Commun. ACM* 63, 12 (2020), 92–99.

[9] Nivedita Arora, Qiuyue Xue, Dhruva Bansal, Peter McAughan, Ryan Bahr, Diego Osorio, Xiaomeng Ma, Alanson P. Sample, Thad E. Starner, and Gregory D. Abowd. 2019. Surface++: A Scalable and Self-sustainable Wireless Sound Sensing Surface (poster). In *Proceedings of the 17th Annual International Conference on Mobile Systems, Applications, and Services* (Seoul, Republic of Korea) *(MobiSys '19)*. Association for Computing Machinery, New York, NY, USA, 543–544. https://doi.org/10.1145/3307334.3328615

[10] Nivedita Arora, Steven L Zhang, Fereshteh Shahmiri, Diego Osorio, Yi-Cheng Wang, Mohit Gupta, Zhengjun Wang, Thad Starner, Zhong Lin Wang, and Gregory D Abowd. 2018. SATURN: A thin and flexible self-powered microphone leveraging triboelectric nanogenerator. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 2 (2018), 1–28.

[11] Rachel Ann Arredondo, Ofri Dar, Kylon Chiang, Arielle Blonder, and Lining Yao. 2022. Blue Ceramics: Co-designing Morphing Ceramics for Seagrass Meadow Restoration. In *Proceedings of the 14th Conference on Creativity and Cognition* (Venice, Italy) *(CC '22)*. Association for Computing Machinery, New York, NY, USA, 392–405. https://doi.org/10.1145/3527927.3531453

[12] Vicente Arroyos, Maria L K Viitaniemi, Nicholas Keehn, Vaidehi Oruganti, Winston Saunders, Karin Strauss, Vikram Iyer, and Bichlien H Nguyen. 2022. A Tale of Two Mice: Sustainable Electronics Design and Prototyping. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI EA '22)*. Association for Computing Machinery, New York, NY, USA, Article 263, 10 pages. https://doi.org/10.1145/3491101.3519823

[13] Lotte Asveld, Patricia Osseweijer, and John A. Posada. 2020. Societal and Ethical Issues in Industrial Biotechnology. In *Sustainability and Life Cycle Assessment in Industrial Biotechnology*, Magnus Fröhling and Michael Hiete (Eds.). Springer International Publishing, Cham, 121–141. https://doi.org/10.1007/10_2019_100

[14] CA Bakker, Renee Wever, Ch Teoh, and Sander De Clercq. 2010. Designing cradle-to-cradle products: a reality check. *International Journal of Sustainable Engineering* 3, 1 (2010), 2–8.

[15] Fiona Bell, Latifa Al Naimi, Ella McQuaid, and Mirela Alistar. 2022. Designing with Alganyl. In *Proceedings of the Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Daejeon, Republic of Korea) *(TEI '22)*. Association for Computing Machinery, New York, NY, USA, Article 2, 14 pages. https://doi.org/10.1145/3490149.3501308

[16] Fiona Bell, Derrek Chow, Hyelin Choi, and Mirela Alistar. 2023. SCOBY BREASTPLATE: SLOWLY GROWING A MICROBIAL INTERFACE. In *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction* (Warsaw, Poland) *(TEI '23)*. Association for Computing Machinery, New York, NY, USA, Article 34, 15 pages. https://doi.org/10.1145/3569009.3572805

[17] Fiona Bell, Derrek Chow, Eldy S. Lazaro Vasquez, Laura Devendorf, and Mirela Alistar. 2023. Designing Interactions with Kombucha SCOBY. In *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction* (Warsaw, Poland) *(TEI '23)*. Association for Computing Machinery, New York, NY, USA, Article 65, 5 pages. https://doi.org/10.1145/3569009.3571841

[18] Fiona Bell, Netta Ofer, and Mirela Alistar. 2022. ReClaym our Compost: Biodegradable Clay for Intimate Making. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 454, 15 pages. https://doi.org/10.1145/3491102.3517711

[19] Fiona Bell, Netta Ofer, Ethan Frier, Ella McQuaid, Hyelin Choi, and Mirela Alistar. 2022. Biomaterial Playground: Engaging with Bio-based Materiality. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI EA '22)*. Association for Computing Machinery, New York, NY, USA, Article 171, 5 pages. https://doi.org/10.1145/3491101.3519875

[20] Fiona Bell, Michelle Ramsahoye, Joshua Coffie, Julia Tung, and Mirela Alistar. 2023. µMe: Exploring the Human Microbiome as an Intimate Material for Living Interfaces. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference* (Pittsburgh, PA, USA) *(DIS '23)*. Association for Computing Machinery, New York, NY, USA, 2019–2033. https://doi.org/10.1145/3563657.3596133

[21] Jane Bennett. 2020. *Vibrant matter: A political ecology of things.* Duke University Press.

[22] Eli Blevis. 2007. Sustainable interaction design: invention & disposal, renewal & reuse. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '07)*. Association for Computing Machinery, New York, NY, USA, 503–512. https://doi.org/10.1145/1240624.1240705

[23] Harold F Blum. 1961. On the origin and evolution of living machines. *American Scientist* 49, 4 (1961), 474–501.

[24] Leonardo Bonanni, Daniela K. Busse, John C. Thomas, Eli Blevis, Marko Turpeinen, and Nuno Jardim Nunes. 2011. Visible - actionable - sustainable: sustainable interaction design in professional domains. In *CHI '11 Extended Abstracts on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI EA '11)*. Association for Computing Machinery, New York, NY, USA, 2413–2416. https://doi.org/10.1145/1979742.1979572

[25] Laetitia Bornes. 2023. A Methodology and a Tool to Support the Sustainable Design of Interactive Systems: Adapting systemic design tools to model complexity in interaction design. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI EA '23)*. Association for Computing Machinery, New York, NY, USA, Article 481, 5 pages. https://doi.org/10.1145/3544549.3577055

[26] Alan Borning, Batya Friedman, and Nick Logler. 2020. The 'invisible' materiality of information technology. *Commun. ACM* 63, 6 (May 2020), 57–64. https://doi.org/10.1145/3360647

[27] Leah Buechley and Ruby Ta. 2023. 3D Printable Play-Dough: New Biodegradable Materials and Creative Possibilities for Digital Fabrication. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 850, 15 pages. https://doi.org/10.1145/3544548.3580813

[28] Alice Buso, Holly McQuillan, Milou Voorwinden, and Elvin Karana. 2023. Weaving Textile-form Interfaces: A Material-Driven Design Journey. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference* (Pittsburgh, PA, USA) *(DIS '23)*. Association for Computing Machinery, New York, NY, USA, 608–622. https://doi.org/10.1145/3563657.3596086

[29] Serena Camere and Elvin Karana. 2018. Fabricating materials from living organisms: An emerging design practice. *Journal of Cleaner Production* 186 (2018), 570–584.

[30] Kimberly Camrass. 2020. Regenerative futures. *foresight* 22, 4 (2020), 401–415.

[31] Fritjof Capra. 2014. *The Systems View of Life: A Unifying Vision.* Cambridge University Press.

[32] Fabrizio Ceschin and Idil Gaziulusoy. 2016. Evolution of design for sustainability: From product design to design for system innovations and transitions. *Design studies* 47 (2016), 118–163.

[33] Martin Charter. 2018. *Designing for the circular economy.* Routledge.

[34] Mrudul Chellapurath, Pranav C Khandelwal, and Andrew K Schulz. 2023. Bioinspired robots can foster nature conservation. *Frontiers in Robotics and AI* 10 (2023), 1145798.

[35] Tingyu Cheng, Taylor Tabb, Jung Wook Park, Eric M Gallo, Aditi Maheshwari, Gregory D. Abowd, Hyunjoo Oh, and Andreea Danielescu. 2023. Functional Destruction: Utilizing Sustainable Materials' Physical Transiency for Electronics Applications. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 366, 16 pages. https://doi.org/10.1145/3544548.3580811

[36] Tingyu Cheng, Zhihan Zhang, Han Huang, Yingting Gao, Wei Sun, Gregory D. Abowd, HyunJoo Oh, and Josiah Hester. 2024. Recy-ctronics: Designing Fully Recyclable Electronics With Varied Form Factors. arXiv:2406.09611 [cs.HC] https://arxiv.org/abs/2406.09611

[37] E.J. Christie, Daniel Jensen, R.T. Buckley, D.A. Menefee, Kyle Ziegler, and Kristin Wood. 2012. Prototyping Strategies: Literature Review and Identification of Critical Variables. *ASEE Annual Conference and Exposition, Conference Proceedings.* https://doi.org/10.18260/1-2--21848

[38] Adrian K. Clear, Chris Preist, Somya Joshi, Lisa P. Nathan, Samuel Mann, and Bonnie A. Nardi. 2015. Expanding the Boundaries: A SIGCHI HCI & Sustainability Workshop. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI EA '15)*. Association for Computing Machinery, New York, NY, USA, 2373–2376. https://doi.org/10.1145/2702613.2702633

[39] Raymond J Cole. 2012. Transitioning from green to regenerative design. *Building Research & Information* 40, 1 (2012), 39–53.

[40] Karijn Den Teuling, Amy Winters, and Miguel Bruns. 2024. Chitosan Biofilm Actuators: Humidity Responsive Materials for Sustainable Interaction Design. In *Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Cork, Ireland) *(TEI '24)*. Association for Computing Machinery, New York, NY, USA, Article 81, 7 pages. https://doi.org/10.1145/3623509.3635262

[41] Himani Deshpande, Haruki Takahashi, and Jeeeun Kim. 2024. Unmake to Remake: Materiality-driven Rapid Prototyping. *ACM Trans. Comput.-Hum. Interact.* (Aug. 2024). https://doi.org/10.1145/3685270 Just Accepted.

[42] Kristin N Dew. 2019. *Exploring Sustainable Materials through Interaction Design Practice.* Ph. D. Dissertation. University of Washington.

[43] Arindam Dey, Mark Billinghurst, Robert W Lindeman, and J Edward Swan. 2018. A systematic review of 10 years of augmented reality usability studies: 2005 to 2014. *Frontiers in Robotics and AI* 5 (2018), 37.

[44] Carl DiSalvo, Phoebe Sengers, and Hrönn Brynjarsdóttir. 2010. Mapping the landscape of sustainable HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Atlanta, Georgia, USA) *(CHI '10)*. Association for Computing Machinery, New York, NY, USA, 1975–1984. https://doi.org/10.1145/1753326.1753625

[45] Chrisna Du Plessis and Raymond J Cole. 2011. Motivating change: shifting the paradigm. *Building research & information* 39, 5 (2011), 436–449.

[46] S Duarte Poblete, Laura Anselmi, Valentina Rognoli, et al. 2023. Emerging materials fostering interdisciplinary collaboration in Materials Design. In *Interdisciplinary Practice in Industrial Design.* AHFE Open Access, 119–129.

[47] Stephen J Eichhorn and Alessandro Gandini. 2010. Materials from renewable resources. *Mrs Bulletin* 35, 3 (2010), 187–193.

[48] Elina Eriksson, Daniel Pargman, Oliver Bates, Maria Normark, Jan Gulliksen, Mikael Anneroth, and Johan Berndtsson. 2016. HCI and UN's Sustainable Development Goals: Responsibilities, Barriers and Opportunities. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (Gothenburg, Sweden) *(NordiCHI '16)*. Association for Computing Machinery, New York, NY, USA, Article 140, 2 pages. https://doi.org/10.1145/2971485.2987679

[49] Arturo Escobar. 2018. *Designs for the pluriverse: Radical interdependence, autonomy, and the making of worlds.* Duke University Press.

[50] Lorena Farías-Cepeda, Lucero Rosales Marines, Anilú Rubio Rios, Victor A Cepeda Tovar, Karina Y Reyes Acosta, and Bertha T Pérez-Martínez. 2023. Biodegradable Foams. *Biodegradable Polymers: Concepts and Applications* (2023), 160.

[51] Ylva Fernaeus and Petra Sundström. 2012. The material move how materials matter in interaction design research. In *Proceedings of the Designing Interactive Systems Conference* (Newcastle Upon Tyne, United Kingdom) *(DIS '12)*. Association for Computing Machinery, New York, NY, USA, 486–495. https://doi.org/10.1145/2317956.2318029

[52] Walter Fieuw, Marcus Foth, and Glenda Amayo Caldwell. 2022. Towards a more-than-human approach to smart and sustainable urban development: Designing for multispecies justice. *Sustainability* 14, 2 (2022), 948.

[53] Laura Forlano. 2017. Posthumanism and design. *She Ji: The Journal of Design, Economics, and Innovation* 3, 1 (2017), 16–29.

[54] Lin Gao, M Usman Akhtar, Fan Yang, Shahzad Ahmad, Jiankang He, Qin Lian, Wei Cheng, Jinhua Zhang, and Dichen Li. 2021. Recent progress in engineering functional biohybrid robots actuated by living cells. *Acta Biomaterialia* 121 (2021), 29–40.

[55] Idil Gaziulusoy and Elif Erdogan Öztekin. 2018. Design as a catalyst for sustainability transitions. In *Design Research Society International Conference*. Design Research Society, 1041–1051.

[56] Elisa Giaccardi and Elvin Karana. 2015. Foundations of Materials Experience: An Approach for HCI. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2447–2456. https://doi.org/10.1145/2702123.2702337

[57] Elisa Giaccardi, Johan Redström, and Iohanna Nicenboim. 2024. The making (s) of more-than-human design: introduction to the special issue on more-than-human design and HCI. , 16 pages.

[58] Phillip Gough, Praneeth Bimsara Perera, Michael A. Kertesz, and Anusha Withana. 2023. Design, Mould, Grow!: A Fabrication Pipeline for Growing 3D Designs Using Myco-Materials. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 851, 15 pages. https://doi.org/10.1145/3544548.3580958

[59] Shad Gross, Jeffrey Bardzell, and Shaowen Bardzell. 2014. Structures, forms, and stuff: the materiality and medium of interaction. *Personal and Ubiquitous Computing* 18 (2014), 637–649.

[60] Eduard Georges Groutars, Raphael Kim, and Elvin Karana. 2024. Designing living artefacts for multispecies interactions: An ecological approach. *International Journal of Design* 18, 2 (2024), 59–78.

[61] Eduard Georges Groutars, Carmen Clarice Risseeuw, Colin Ingham, Raditijo Hamidjaja, Willemijn S. Elkhuizen, Sylvia C. Pont, and Elvin Karana. 2022. 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* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 99, 19 pages. https://doi.org/10.1145/3491102.3517713

[62] Sofía Guridi, Emmi Pouta, Ari Hokkanen, and Aayush Jaiswal. 2023. LIGHT TISSUE: Development of cellulose-based optical textile sensors. In *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction* (Warsaw, Poland) *(TEI '23)*. Association for Computing Machinery, New York, NY, USA, Article 27, 14 pages. https://doi.org/10.1145/3569009.3572798

[63] Mira Alida Haberfellner, Samuel Zühlke, Leopold Boess, Kathrin Probst, and Michael Haller. 2024. Threads of Traceability: Textile IDs in the Fabric of Sustainable Fashion. In *Proceedings of the 2024 ACM Designing Interactive Systems Conference* (Copenhagen, Denmark) *(DIS '24)*. Association for Computing Machinery, New York, NY, USA, 3063–3078. https://doi.org/10.1145/3643834.3661531

[64] Lon Åke Erni Johannes Hansson, Teresa Cerratto Pargman, and Daniel Sapiens Pargman. 2021. A Decade of Sustainable HCI: Connecting SHCI to the Sustainable Development Goals. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 300, 19 pages. https://doi.org/10.1145/3411764.3445069

[65] Ollie Hanton, Zichao Shen, Mike Fraser, and Anne Roudaut. 2022. FabricatINK: Personal Fabrication of Bespoke Displays Using Electronic Ink from Upcycled E Readers. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 173, 15 pages. https://doi.org/10.1145/3491102.3501844

[66] Brosl Hasslacher and Mark W Tilden. 1995. Living machines. *Robotics and autonomous systems* 15, 1-2 (1995), 143–169.

[67] Dominique Hes and Chrisna Du Plessis. 2014. *Designing for hope: Pathways to regenerative sustainability.* Routledge.

[68] Yuta Ikeya, Ron Wakkary, and Bahareh Barati. 2023. Metamorphonic: A Reflective Design Inquiry into Human-Silkworm Relationship. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference* (Pittsburgh, PA, USA) *(DIS '23)*. Association for Computing Machinery, New York, NY, USA, 808–819. https://doi.org/10.1145/3563657.3596053

[69] Vikram Iyer, Hans Gaensbauer, Thomas L Daniel, and Shyamnath Gollakota. 2022. Wind dispersal of battery-free wireless devices. *Nature* 603, 7901 (2022), 427–433.

[70] Tim Jackson. 2009. *Prosperity without growth: Economics for a finite planet.* Routledge.

[71] A Jahan, Md Yusof Ismail, SM Sapuan, and F Mustapha. 2010. Material screening and choosing methods–a review. *Materials & Design* 31, 2 (2010), 696–705.

[72] Heekyoung Jung and Erik Stolterman. 2012. 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.* 645–654.

[73] Elvin Karana, Bahareh Barati, Valentina Rognoli, Anouk Zeeuw Van Der Laan, et al. 2015. Material driven design (MDD): A method to design for material experiences. *International journal of design* 9, 2 (2015), 35–54.

[74] Elvin Karana, PPM Hekkert, and PV Kandachar. 2008. Materials experience: descriptive categories in materials appraisals. In *Seventh International Symposium on Tools and Methods of Competitive Engineering-TMCE 2008, Izmir, Turkey*. Delft University of Technology/Middle East Technical University, 1–15.

[75] Elvin Karana, Holly McQuillan, Valentina Rognoli, and Elisa Giaccardi. 2023. Living artefacts for regenerative ecologies. *Research Directions: Biotechnology Design* 1 (2023), e16.

[76] Elvin Karana, Owain Pedgley, and Valentina Rognoli. 2013. *Materials experience: Fundamentals of materials and design.* Butterworth-Heinemann.

[77] Emily Kennedy, Daphne Fecheyr-Lippens, Bor-Kai Hsiung, Peter H Niewiarowski, and Matthew Kolodziej. 2015. Biomimicry: A path to sustainable innovation. *Design Issues* 31, 3 (2015), 66–73.

[78] Rushil Khurana and Steve Hodges. 2020. Beyond the Prototype: Understanding the Challenge of Scaling Hardware Device Production. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3313831.3376761

[79] Hyun Chan Kim, Seongcheol Mun, Hyun-U Ko, Lindong Zhai, Abdullahil Kafy, and Jaehwan Kim. 2016. Renewable smart materials. *Smart Materials and Structures* 25, 7 (2016), 073001.

[80] Bran Knowles, Oliver Bates, and Maria Håkansson. 2018. This Changes Sustainable HCI. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3174045

[81] Bran Knowles, Adrian K. Clear, Samuel Mann, Eli Blevis, and Maria Håkansson. 2016. Design Patterns, Principles, and Strategies for Sustainable HCI. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI EA '16)*. Association for Computing Machinery, New York, NY, USA, 3581–3588. https://doi.org/10.1145/2851581.2856497

[82] Marion Koelle, Madalina Nicolae, Aditya Shekhar Nittala, Marc Teyssier, and Jürgen Steimle. 2022. Prototyping Soft Devices with Interactive Bioplastics. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 19, 16 pages. https://doi.org/10.1145/3526113.3545623

[83] Louis J Kotzé, Rakhyun E Kim, Peter Burdon, Louise Du Toit, Lisa-Maria Glass, Prakash Kashwan, Diana Liverman, Francesco S Montesano, Salla Rantala, Carole-Anne Sénit, et al. 2022. Planetary integrity. In *The political impact of the sustainable development goals: Transforming governance through global goals?* Cambridge University Press, 140.

[84] Agathoklis A Krimpenis and Georgios D Noeas. 2022. Application of Hybrid Manufacturing processes in microfabrication. *Journal of Manufacturing Processes* 80 (2022), 328–346.

[85] Morphing Matter Lab. 2024. Special Interest Group, CHI'24. Ecological HCI: Reflection and Future. https://morphingmatter.org/chisig [Accessed: 2024-10-11].

[86] Eldy S. Lazaro Vasquez, Lily M Gabriel, Mikhaila Friske, Shanel Wu, Sasha De Koninck, Laura Devendorf, and Mirela Alistar. 2023. Designing Dissolving Wearables. In *Adjunct Proceedings of the 2023 ACM International Joint Conference on Pervasive and Ubiquitous Computing & the 2023 ACM International Symposium on Wearable Computing* (Cancun, Quintana Roo, Mexico) *(UbiComp/ISWC '23 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 286–290. https://doi.org/10.1145/3594739.3610781

[87] Eldy S. Lazaro Vasquez, Netta Ofer, Shanel Wu, Mary Etta West, Mirela Alistar, and Laura Devendorf. 2022. Exploring Biofoam as a Material for Tangible Interaction. In *Proceedings of the 2022 ACM Designing Interactive Systems Conference* (Virtual Event, Australia) *(DIS '22)*. Association for Computing Machinery, New York, NY, USA, 1525–1539. https://doi.org/10.1145/3532106.3533494

[88] Yujun Lin and Jeyeon Jo. 2024. LeatherBoard: Sustainable On-body Rapid Prototyping with Leather Scraps and Machine Embroidery. In *Extended Abstracts of the 2024 CHI Conference on Human Factors in Computing Systems (CHI EA '24)*. Association for Computing Machinery, New York, NY, USA, Article 221, 7 pages. https://doi.org/10.1145/3613905.3650894

[89] Iban Lizarralde and Benjamin Tyl. 2018. A framework for the integration of the conviviality concept in the design process. *Journal of Cleaner Production* 197 (2018), 1766–1777.

[90] Jasmine Lu, Beza Desta, K. D. Wu, Romain Nith, Joyce E Passananti, and Pedro Lopes. 2023. ecoEDA: Recycling E-waste During Electronics Design. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 30, 14 pages. https://doi.org/10.1145/3586183.3606745

[91] Jasmine Lu and Pedro Lopes. 2022. Integrating Living Organisms in Devices to Implement Care-based Interactions. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 28, 13 pages. https://doi.org/10.1145/3526113.3545629

[92] Qiuyu Lu, Andreea Danielescu, Vikram Iyer, Pedro Lopes, and Lining Yao. 2024. Ecological HCI: Reflection and Future. In *Extended Abstracts of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '24)*. Association for Computing Machinery, New York, NY, USA, Article 577, 4 pages. https://doi.org/10.1145/3613905.3643985

[93] Qiuyu Lu, Jifei Ou, Lining Yao, and Hiroshi Ishii. 2024. milleCrepe: Extending Capabilities of Fluid-driven Interfaces with Multilayer Structures and Diverse Actuation Media. In *Extended Abstracts of the 2024 CHI Conference on Human Factors in Computing Systems (CHI EA '24)*. Association for Computing Machinery, New York, NY, USA, Article 383, 10 pages. https://doi.org/10.1145/3613905.3650891

[94] Qiuyu Lu, Lydia Yang, Aditi Maheshwari, Hengrong Ni, Tianyu Yu, Jianzhe Gu, Advait Wadhwani, Haiqing Xu, Andreea Danielescu, and Lining Yao. 2024. Guttation Sensor: Wearable Microfluidic Chip for Plant Condition Monitoring and Diagnosis. In *Extended Abstracts of the 2024 CHI Conference on Human Factors in Computing Systems (CHI EA '24)*. Association for Computing Machinery, New York, NY, USA, Article 183, 9 pages. https://doi.org/10.1145/3613905.3651087

[95] Qiuyu Lu, Semina Yi, Mengtian Gan, Jihong Huang, Xiao Zhang, Yue Yang, Chenyi Shen, and Lining Yao. 2024. Degrade to Function: Towards Eco-friendly Morphing Devices that Function Through Programmed Sequential Degradation. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology* (Pittsburgh, PA, USA) *(UIST '24)*. Association for Computing Machinery, New York, NY, USA, Article 109, 24 pages. https://doi.org/10.1145/3654777.3676464

[96] Qiuyu Lu, Tianyu Yu, Semina Yi, Yuran Ding, Haipeng Mi, and Lining Yao. 2023. Sustainflatable: Harvesting, Storing and Utilizing Ambient Energy for Pneumatic Morphing Interfaces. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 32, 20 pages. https://doi.org/10.1145/3586183.3606721

[97] Danli Luo, Jianzhe Gu, Fang Qin, Guanyun Wang, and Lining Yao. 2020. E-seed: Shape-Changing Interfaces that Self Drill. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 45–57. https://doi.org/10.1145/3379337.3415855

[98] Danli Luo, Aditi Maheshwari, Andreea Danielescu, Jiaji Li, Yue Yang, Ye Tao, Lingyun Sun, Dinesh K Patel, Guanyun Wang, Shu Yang, et al. 2023. Autonomous self-burying seed carriers for aerial seeding. *Nature* 614, 7948 (2023), 463–470.

[99] Ellen MacArthur et al. 2013. Towards the circular economy. *Journal of Industrial Ecology* 2, 1 (2013), 23–44.

[100] Pamela Mang and Bill Reed. 2012. Designing from place: A regenerative framework and methodology. *Building Research & Information* 40, 1 (2012), 23–38.

[101] Pamela Mang and Bill Reed. 2020. Regenerative development and design. *Sustainable built environments* (2020), 115–141.

[102] Jennifer Mankoff. 2012. HCI and sustainability: a tale of two motivations. *Interactions* 19, 3 (2012), 16–19.

[103] Jennifer C. Mankoff, Eli Blevis, Alan Borning, Batya Friedman, Susan R. Fussell, Jay Hasbrouck, Allison Woodruff, and Phoebe Sengers. 2007. Environmental sustainability and interaction. In *CHI '07 Extended Abstracts on Human Factors in Computing Systems* (San Jose, CA, USA) *(CHI EA '07)*. Association for Computing Machinery, New York, NY, USA, 2121–2124. https://doi.org/10.1145/1240866.1240963

[104] Holly McQuillan and Elvin Karana. 2023. 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* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 727, 19 pages. https://doi.org/10.1145/3544548.3581156

[105] Yogesh Kumar Meena, Xing-Dong Yang, Markus Löchtefeld, Matt Carnie, Niels Henze, Steve Hodges, Matt Jones, Nivedita Arora, and Gregory D. Abowd. 2020. SelfSustainableCHI: Self-Powered Sustainable Interfaces and Interactions. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–7. https://doi.org/10.1145/3334480.3375167

[106] Eleonora Mencarini, Christina Bremer, Chiara Leonardi, Jen Liu, Valentina Nisi, Nuno Jardim Nunes, and Robert Soden. 2023. HCI for Climate Change: Imagining Sustainable Futures. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI EA '23)*. Association for Computing Machinery, New York, NY, USA, Article 352, 6 pages. https://doi.org/10.1145/3544549.3573833

[107] Galina Mihaleva, Abigail Dalton, Mary Fitzgerald, and Abhik Chowdhury. 2023. Haikeus: Transmuting Ecological Grieving into Action. In *Adjunct Proceedings of the 2023 ACM International Joint Conference on Pervasive and Ubiquitous Computing & the 2023 ACM International Symposium on Wearable Computing* (Cancun, Quintana Roo, Mexico) *(UbiComp/ISWC '23 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 301–303. https://doi.org/10.1145/3594739.3610784

[108] Harold A Mooney and Elsa E Cleland. 2001. The evolutionary impact of invasive species. *Proceedings of the National Academy of Sciences* 98, 10 (2001), 5446–5451.

[109] Bonnie Nardi, Bill Tomlinson, Donald J. Patterson, Jay Chen, Daniel Pargman, Barath Raghavan, and Birgit Penzenstadler. 2018. Computing within limits. *Commun. ACM* 61, 10 (Sept. 2018), 86–93. https://doi.org/10.1145/3183582

[110] Madalina Nicolae, Claire Lefez, Anne Roudaut, Samuel Huron, Jürgen Steimle, and Marc Teyssier. 2024. SoftBioMorph: Fabricating Sustainable Shape-changing Interfaces using Soft Biopolymers. In *Proceedings of the 2024 ACM Designing Interactive Systems Conference* (Copenhagen, Denmark) *(DIS '24)*. Association for Computing Machinery, New York, NY, USA, 496–508. https://doi.org/10.1145/3643834.3661610

[111] Madalina Nicolae, Vivien Roussel, Marion Koelle, Samuel Huron, Jürgen Steimle, and Marc Teyssier. 2023. Biohybrid Devices: Prototyping Interactive Devices with Growable Materials. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 31, 15 pages. https://doi.org/10.1145/3586183.3606774

[112] Netta Ofer and Mirela Alistar. 2023. Felt Experiences with Kombucha Scoby: Exploring First-person Perspectives with Living Matter. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 477, 18 pages. https://doi.org/10.1145/3544548.3581276

[113] Netta Ofer, Fiona Bell, and Mirela Alistar. 2021. Designing Direct Interactions with Bioluminescent Algae. In *Proceedings of the 2021 ACM Designing Interactive Systems Conference* (Virtual Event, USA) *(DIS '21)*. Association for Computing Machinery, New York, NY, USA, 1230–1241. https://doi.org/10.1145/3461778.3462090

[114] Stefano Parisi, Valentina Rognoli, and Marieke Sonneveld. 2017. Material Tinkering. An inspirational approach for experiential learning and envisioning in product design education. *The Design Journal* 20, sup1 (2017), S1167–S1184.

[115] Pat Pataranutaporn, Todd Ingalls, and Ed Finn. 2018. Biological HCI: Towards Integrative Interfaces Between People, Computer, and Biological Materials. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI EA '18)*. Association for Computing Machinery, New York, NY, USA, 1–6. https://doi.org/10.1145/3170427.3188662

[116] Pat Pataranutaporn, Angela Vujic, David S Kong, Pattie Maes, and Misha Sra. 2020. Living bits: Opportunities and challenges for integrating living microorganisms in human-computer interaction. In *Proceedings of the augmented humans international conference*. 1–12.

[117] Dinesh K Patel, Ke Zhong, Haiqing Xu, Mohammad F Islam, and Lining Yao. 2023. Sustainable morphing matter: design and engineering practices. *Advanced Materials Technologies* 8, 23 (2023), 2300678.

[118] Joana Castro Pereira, Carlota Houart, Mariana Riquito, Vera Ferreira, Lorenzo Feltrin, Emanuele Leonardi, Thais Lemos Ribeiro, and Verônica Korber Gonçalves. 2023. The challenge of the global ecological crisis for world politics. *The challenge of the global ecological crisis for world politics* (2023), 1.

[119] Sarah Pink, Kerstin Leder Mackley, Val Mitchell, Marcus Hanratty, Carolina Escobar-Tello, Tracy Bhamra, and Roxana Morosanu. 2013. Applying the lens of sensory ethnography to sustainable HCI. *ACM Transactions on Computer-Human Interaction (TOCHI)* 20, 4 (2013), 1–18.

[120] Sofia Soledad Duarte Poblete, Alessia Romani, and Valentina Rognoli. 2024. Emerging materials for transition: A taxonomy proposal from a design perspective. *Sustainable Futures* 7 (2024), 100155.

[121] Tony J Prescott, Nathan Lepora, and Paul FM J Verschure. 2018. *Living machines: A handbook of research in biomimetics and biohybrid systems.* Oxford University Press.

[122] Tony J Prescott, Nathan Lepora, and Paul FMJ Vershure. 2014. A future of living machines?: International trends and prospects in biomimetic and biohybrid systems. *Bioinspiration, Biomimetics, and Bioreplication 2014* 9055 (2014), 905502.

[123] Isabel P. S. Qamar, Rainer Groh, David Holman, and Anne Roudaut. 2018. HCI meets Material Science: A Literature Review of Morphing Materials for the Design of Shape-Changing Interfaces. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–23. https://doi.org/10.1145/3173574.3173948

[124] Tucker Rae-Grant, Shuhong Wang, and Lining Yao. 2024. ExCell: High Expansion Ratio Moisture-Responsive Wooden Actuators for DIY Shape-Changing and Deployable Structures. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 516, 14 pages. https://doi.org/10.1145/3613904.3642565

[125] Bill Reed. 2007. Shifting from 'sustainability'to regeneration. *Building Research & Information* 35, 6 (2007), 674–680.

[126] Christian Remy, Oliver Bates, Alan Dix, Vanessa Thomas, Mike Hazas, Adrian Friday, and Elaine M. Huang. 2018. Evaluation Beyond Usability: Validating Sustainable HCI Research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3173574.3173790

[127] Christian Remy, Silke Gegenbauer, and Elaine M. Huang. 2015. Bridging the Theory-Practice Gap: Lessons and Challenges of Applying the Attachment Framework for Sustainable HCI Design. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 1305–1314. https://doi.org/10.1145/2702123.2702567

[128] Miriam Ribul, Kate Goldsworthy, and Carole Collet. 2021. Material-Driven Textile Design (MDTD): A methodology for designing circular material-driven fabrication and finishing processes in the materials science laboratory. *Sustainability* 13, 3 (2021), 1268.

[129] William J Ripple, Christopher Wolf, Thomas M Newsome, Phoebe Barnard, and William R Moomaw. 2020. World scientists' warning of a climate emergency. *BioScience* 70, 1 (2020), 8–100.

[130] Clarice Risseeuw, Holly Mcquillan, Joana Martins, and Elvin Karana. 2024. (Re)activate, (Re)direct, (Re)arrange: Exploring the Design Space of Direct Interactions with Flavobacteria. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 705, 18 pages. https://doi.org/10.1145/3613904.3642262

[131] Michael L. Rivera, S. Sandra Bae, and Scott E. Hudson. 2023. Designing a Sustainable Material for 3D Printing with Spent Coffee Grounds. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference* (Pittsburgh, PA, USA) *(DIS '23)*. Association for Computing Machinery, New York, NY, USA, 294–311. https://doi.org/10.1145/3563657.3595983

[132] Alessia Romani, Francesca Casnati, and Alessandro Ianniello. 2022. Codesign with more-than-humans: toward a meta co-design tool for human-non-human collaborations. *European Journal of Futures Research* 10, 1 (2022), 17.

[133] Daniela K. Rosner, Miwa Ikemiya, Diana Kim, and Kristin Koch. 2013. Designing with traces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Paris, France) *(CHI '13)*. Association for Computing Machinery, New York, NY, USA, 1649–1658. https://doi.org/10.1145/2470654.2466218

[134] Ann K Sakai, Fred W Allendorf, Jodie S Holt, David M Lodge, Jane Molofsky, Kimberly A With, Syndallas Baughman, Robert J Cabin, Joel E Cohen, Norman C Ellstrand, et al. 2001. The population biology of invasive species. *Annual review of ecology and systematics* 32, 1 (2001), 305–332.

[135] Vishal Sharma, Neha Kumar, and Bonnie Nardi. 2023. Post-growth Human–Computer Interaction. *ACM Trans. Comput.-Hum. Interact.* 31, 1, Article 9 (Nov. 2023), 37 pages. https://doi.org/10.1145/3624981

[136] Vishal Sharma, Anupriya Tuli, Asra Sakeen Wani, Anjali Karol Mohan, Bonnie Nardi, Marc Hassenzahl, Morgan Vigil-Hayes, Rikke Hagensby Jensen, Shaowen Bardzell, and Neha Kumar. 2024. Post-growth HCI: Co-Envisioning HCI Beyond Economic Growth. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '24)*. Association for Computing Machinery, New York, NY, USA, Article 486, 7 pages. https://doi.org/10.1145/3613905.3636292

[137] M. Six Silberman, Eli Blevis, Elaine Huang, Bonnie A. Nardi, Lisa P. Nathan, Daniela Busse, Chris Preist, and Samuel Mann. 2014. What have we learned? a SIGCHI HCI & sustainability community workshop. In *CHI '14 Extended Abstracts on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 143–146. https://doi.org/10.1145/2559206.2559238

[138] M Six Silberman, Lisa Nathan, Bran Knowles, Roy Bendor, Adrian Clear, Maria Håkansson, Tawanna Dillahunt, and Jennifer Mankoff. 2014. Next steps for sustainable HCI. *interactions* 21, 5 (2014), 66–69.

[139] Katherine W Song, Aditi Maheshwari, Eric M Gallo, Andreea Danielescu, and Eric Paulos. 2022. Towards Decomposable Interactive Systems: Design of a Backyard-Degradable Wireless Heating Interface. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 100, 12 pages. https://doi.org/10.1145/3491102.3502007

[140] Katherine W Song and Eric Paulos. 2021. Unmaking: Enabling and Celebrating the Creative Material of Failure, Destruction, Decay, and Deformation. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 429, 12 pages. https://doi.org/10.1145/3411764.3445529

[141] Katherine Wei Song and Eric Paulos. 2023. Vim: Customizable, Decomposable Electrical Energy Storage. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 180, 18 pages. https://doi.org/10.1145/3544548.3581110

[142] Clive L Spash. 2015. The future post-growth society. *Development and Change* 46, 2 (2015), 366–380.

[143] Yolande A.A. Strengers. 2011. Designing eco-feedback systems for everyday life. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 2135–2144. https://doi.org/10.1145/1978942.1979252

[144] Lingyu Sun, Yunru Yu, Zhuoyue Chen, Feika Bian, Fangfu Ye, Lingyun Sun, and Yuanjin Zhao. 2020. Biohybrid robotics with living cell actuation. *Chemical Society Reviews* 49, 12 (2020), 4043–4069.

[145] Lee Suzanne, Congdon Amy, Parker Georgia, and Borst Charlotte. 2020. *UNDERSTANDING 'BIO' MATERIAL INNOVATION: a primer for the fashion industry.* Technical Report. Biofabricate and Fashion for Good.

[146] Berilsu Tarcan, Ida Nilstad Pettersen, and Ferne Edwards. 2022. Making-with the environment through more-than-human design. *DRS2022: Bilbao* (2022).

[147] Virginia Tassinari, Ezio Manzini, Arturo Escobar, Liesbeth Huybrechts, Annalinda De Rosa, et al. 2020. The politics of nature. Designing for an ontological turn. DESIS philosophy talk# 7.2. In *Participación (es) Otras/Participation (s) Otherwise (Vol 3)*. Vol. 3. Universidad de Caldas, 488–493.

[148] Shan-Yuan Teng, K. D. Wu, Jacqueline Chen, and Pedro Lopes. 2022. Prolonging VR Haptic Experiences by Harvesting Kinetic Energy from the User. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 39, 18 pages. https://doi.org/10.1145/3526113.3545635

[149] Jakob Tholander, Maria Normark, and Chiara Rossitto. 2012. Understanding agency in interaction design materials. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI '12)*. Association for Computing Machinery, New York, NY, USA, 2499–2508. https://doi.org/10.1145/2207676.2208417

[150] Bill Tomlinson, Eli Blevis, Bonnie Nardi, Donald J. Patterson, M. SIX Silberman, and Yue Pan. 2013. Collapse informatics and practice: Theory, method, and design. *ACM Trans. Comput.-Hum. Interact.* 20, 4, Article 24 (Sept. 2013), 26 pages. https://doi.org/10.1145/2493431

[151] Jane Toner, Cheryl Desha, Kimberley Reis, Dominique Hes, and Samantha Hayes. 2023. Integrating Ecological Knowledge into Regenerative Design: A Rapid Practice Review. *Sustainability* 15, 17 (2023), 13271.

[152] Anna Lowenhaupt Tsing. 2012. On nonscalability: The living world is not amenable to precision-nested scales. *Common knowledge* 18, 3 (2012), 505–524.

[153] Sim Vander Ryn and Sttmt Cowan. 1996. Ecological Design Island Press Washington. *DC Google Scholar* (1996).

[154] Eldy S. Lazaro Vasquez and Katia Vega. 2019. Myco-accessories: sustainable wearables with biodegradable materials. In *Proceedings of the 2019 ACM International Symposium on Wearable Computers* (London, United Kingdom) *(ISWC '19)*. Association for Computing Machinery, New York, NY, USA, 306–311. https://doi.org/10.1145/3341163.3346938

[155] Carlo Vezzoli. 2014. The "material" side of design for sustainability. In *Materials Experience*. Elsevier, 105–121.

[156] Carlo Vezzoli, Ezio Manzini, et al. 2008. *Design for environmental sustainability.* Springer.

[157] Susanna Vogel, Nathalia Campreguer França, Eleni Economidou, Bernhard Maurer, and Manfred Tscheligi. 2020. Circular HCI: Tools for Embedding Circular Thinking in Material-Driven Design. In *Companion Publication of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS' 20 Companion)*. Association for Computing Machinery, New York, NY, USA, 233–237. https://doi.org/10.1145/3393914.3395894

[158] Anandghan Waghmare, Qiuyue Xue, Dingtian Zhang, Yuhui Zhao, Shivan Mittal, Nivedita Arora, Ceara Byrne, Thad Starner, and Gregory D Abowd. 2020. UbiquiTouch: Self sustaining ubiquitous touch interfaces. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 4, 1 (2020), 1–22.

[159] Jennifer Weiler, Piyum Fernando, Nipuni Siyambalapitiya, and Stacey Kuznetsov. 2019. Mycelium Artifacts: Exploring Shapeable and Accessible Biofabrication. In *Companion Publication of the 2019 on Designing Interactive Systems Conference 2019 Companion* (San Diego, CA, USA) *(DIS '19 Companion)*. Association for Computing Machinery, New York, NY, USA, 69–72. https://doi.org/10.1145/3301019.3325156

[160] Irmandy Wicaksono, Aditi Maheshwari, Don Derek Haddad, Joseph Paradiso, and Andreea Danielescu. 2024. Design and Fabrication of Multi-functional E-Textiles by Upcycling Waste Cotton Fabrics through Carbonization. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 8, 2 (2024), 1–31.

[161] E.O. Wilson. 1992. *The Diversity of Life.* Belknap Press of Harvard University Press. https://books.google.fr/books?id=ZSqehqH-qTYC

[162] Zeyu Yan, Tingyu Cheng, Jasmine Lu, Pedro Lopes, and Huaishu Peng. 2023. Future Paradigms for Sustainable Making. In *Adjunct Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23 Adjunct)*. Association for Computing Machinery, New York, NY, USA, Article 109, 3 pages. https://doi.org/10.1145/3586182.3617433

[163] Zeyu Yan, Jiasheng Li, Zining Zhang, and Huaishu Peng. 2024. SolderlessPCB: Reusing Electronic Components in PCB Prototyping through Detachable 3D Printed Housings. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 345, 17 pages. https://doi.org/10.1145/3613904.3642765

[164] Lining Yao, Jifei Ou, Chin-Yi Cheng, Helene Steiner, Wen Wang, Guanyun Wang, and Hiroshi Ishii. 2015. bioLogic: Natto Cells as Nanoactuators for Shape Changing Interfaces. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/2702123.2702611

[165] Bill Yen, Laura Jaliff, Louis Gutierrez, Philothei Sahinidis, Sadie Bernstein, John Madden, Stephen Taylor, Colleen Josephson, Pat Pannuto, Weitao Shuai, et al. 2024. Soil-powered computing: the engineer's guide to practical soil microbial fuel cell design. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 7, 4 (2024), 1–40.

[166] Dingtian Zhang, Canek Fuentes-Hernandez, Raaghesh Vijayan, Yang Zhang, Yunzhi Li, Jung Wook Park, Yiyang Wang, Yuhui Zhao, Nivedita Arora, Ali Mirzazadeh, et al. 2022. Flexible computational photodetectors for self-powered activity sensing. *npj Flexible Electronics* 6, 1 (2022), 7.

[167] Zhihan Zhang, Felix Hähnlein, Yuxuan Mei, Zachary Englhardt, Shwetak Patel, Adriana Schulz, and Vikram Iyer. 2024. DeltaLCA: Comparative Life-Cycle Assessment for Electronics Design. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 8, 1, Article 29 (March 2024), 29 pages. https://doi.org/10.1145/3643561

[168] Zhihan Zhang, Mallory Parker, Kuotian Liao, Jerry Cao, Anandghan Waghmare, Joseph Breda, Chris Matsumura, Serena Eley, Eleftheria Roumeli, Shwetak Patel, et al. 2024. Biodegradable Interactive Materials. *arXiv preprint arXiv:2404.03130* (2024).

[169] Jiwei Zhou, Zjenja Doubrovski, Elisa Giaccardi, and Elvin Karana. 2024. Living with Cyanobacteria: Exploring Materiality in Caring for Microbes in Everyday Life. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 561, 20 pages. https://doi.org/10.1145/3613904.3642039

[170] 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* (Pittsburgh, PA, USA) *(DIS '23)*. Association for Computing Machinery, New York, NY, USA, 820–838. https://doi.org/10.1145/3563657.3596132

[171] Jingwen Zhu, Nadine El Nesr, Christina Simon, Nola Rettenmaier, Kaitlyn Beiler, and Cindy Hsin-Liu Kao. 2023. BioWeave: Weaving Thread-Based Sweat-Sensing On-Skin Interfaces. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 35, 11 pages. https://doi.org/10.1145/3586183.3606769

[172] Jingwen Zhu, Lily Winagle, and Hsin-Liu (Cindy) Kao. 2024. EcoThreads: Prototyping Biodegradable E-textiles Through Thread-based Fabrication. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 857, 17 pages. https://doi.org/10.1145/3613904.3642718

A Basic Information of the Included Studies

Table 1. Basic Information of the Included Studies

Reference	Publication year	Publication venue	ACC
Yao et al.[164]	2015	CHI '15	27.4
Weiler et al.[159]	2019	DIS '19	6.6
Vasquez et al.[154]	2019	UbiComp/ISWC '19	15.6
Luo et al.[97]	2020	UIST '20	2.75
Song et al.[140]	2021	CHI '21	24.3
Ofer et al.[113]	2021	DIS '21	14.7
Arora et al.[7]	2021	UIST '21	6
Bell et al.[18]	2022	CHI '22	19
Groutars et al.[61]	2022	CHI '22	15
Arroyos et al.[12]	2022	CHI '22	15.5
Song et al.[139]	2022	CHI '22	18.5
Lazaro Vasquez et al.[87]	2022	DIS '22	17.5
Bell et al.[15]	2022	TEI '22	18.5
Koelle et al.[82]	2022	UIST '22	19
Lu et al.[91]	2022	UIST '22	15
Arredondo et al.[11]	2022	C&C '22	2
Buechley et al.[27]	2023	CHI '23	24
Gough et al.[58]	2023	CHI '23	10

Song et al.[141]	2023	CHI ’23	14
Ofer et al.[112]	2023	CHI ’23	23
Cheng et al.[35]	2023	CHI ’23	18
Rivera et al.[131]	2023	DIS ’23	20
Zhou et al.[170]	2023	DIS ’23	5
Bell et al.[20]	2023	DIS ’23	13
Guridi et al.[62]	2023	TEI ’23	5
Bell et al.[16]	2023	TEI ’23	26
Zhu et al.[171]	2023	UIST ’23	3
Lu et al.[90]	2023	UIST ’23	16
Nicolae et al.[111]	2023	UIST ’23	6
Lu et al.[96]	2023	UIST ’23	1
Lazaro Vasquez et al.[86]	2023	UbiComp/ISWC ’23	5
Mihaleva et al.[107]	2023	UbiComp/ISWC ’23	1
Risseeuw et al.[130]	2024	CHI ’24	0
Zhou et al.[169]	2024	CHI ’24	0
Zhu et al.[172]	2024	CHI ’24	0
Lin et al.[88]	2024	CHI ’24	0
Rae-Grant et al.[124]	2024	CHI ’24	0
Yan et al.[163]	2024	CHI ’24	0
Lu et al.[94]	2024	CHI ’24	0
Haberfellner et al.[63]	2024	DIS ’24	0
Nicolae et al.[110]	2024	DIS ’24	0
Den Teuling et al.[40]	2024	TEI ’24	0
Lu et al.[95]	2024	UIST ’24	0
Wicaksono et al.[160]	2024	IMWUT	0
Zhang et al.[168]	2024	arXiv	0
Cheng et al.[36]	2024	arXiv	0