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Nicla Guarino
Design Department, Politecnico di Milano, Milan, Italy

Venere Ferraro
Design Department, Politecnico di Milano, Milan, Italy

Valentina Rognoli
Design Department, Politecnico di Milano, Milan, Italy

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Mapping Circular Design pathways for wearables: An annotated portfolio at the intersection of Material-Driven Design and Bio-HCI

Nicla Guarino[a], Venere Ferraro[a], Valentina Rognoli[a]

[a]Design Department, Politecnico di Milano, Milan, Italy

*Corresponding author e-mail: nicla.guarino@polimi.it

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Abstract: As the environmental impacts of wearable technologies intensify, exploring how material choices can enable circularity in such a waste-intensive sector has become critical for design research. In response to this challenge, materials are recognised as pivotal in emerging wearable alternatives, yet how they can actively support circular practices remains underexplored. The study addresses this gap through an annotated portfolio of 40 case studies situated in or informing the wearable domain at the intersection of Material-Driven Design and Bio-HCI. By foregrounding recurring materials, methods, and tools, the analysis aims to reveal how matter can act as a transformative agent in shaping low-impact wearable solutions. Key outcomes include the identification of transferable design principles demonstrating the potential of material-driven and speculative approaches for generating transitional scenarios. The study further advances the dialogue on embodied and symbiotic interactions, emphasising the active role of materials in guiding designers toward circular futures.

Keywords: Wearables; Circular Design; Material-Driven Design; Bio-HCI

1. Introduction

Amid ongoing climate and environmental crises, the material world we inhabit is constantly shaken and reshaped (Peters, 2014). At the same time, the dissolution of boundaries between digital and human realms further exposes the ambivalent condition of materials, at once fragile and full of transformative potential.

Technological pervasiveness is often considered an immaterial dimension (Paul, 2015), giving rise to the idea of a materiality's decline, where matter becomes secondary to intangible streams of data (Geismar, 2018). However, this perspective has been counterbalanced by growing recognition of the digital realm as profoundly material (Parikka, 2015). In this "new materialistic" context, the field of Human-Computer Interaction (HCI) exemplifies a "material turn" (Barad, 2003; Braidotti, 2013; Dourish, 2001, 2004; Haraway, 2010; Wiberg, 2018) where interfaces are approached as tangible mediators of embodied interaction (Ishii & Ullmer, 1997; Ullmer & Ishii, 2000; Vallgårda & Redström, 2007).

Within this post-digital and material-driven perspective, the design of technological devices such as wearables gains renewed significance. Their materiality serves both as a functional physical object and an immediate interface, as well as a potential source of environmental impact if not carefully considered. Intersecting multiple domains – material science, biotechnology, HCI, ICTs, textile design, and fashion design (Minaoglou et al., 2024) – wearables pose greater recycling challenges than other electronics because of their miniaturisation and diverse material composition (Arbaud et al., 2024; Gurova et al., 2020; Timmins, 2009). Circular Economy principles, such as Life Cycle Thinking, Design for Environment, and other Design for X approaches provide promising strategies to mitigate these impacts (He et al., 2024).

In this direction, disciplines such as Materials Design and Material-Driven Design (MDD) have taken a strategic role within the field of Design. These approaches rethink materials, moving beyond neutral, technical sources to objects conveying meanings, identities, and values (Karana et al., 2013; Pedgley et al., 2021). By employing materials as mediators of experience and agents of interaction, such practices address environmental concerns, supporting the transition toward sustainability and circular processes (Duarte Poblete et al., 2024; Giaccardi & Karana, 2015). Building on this MDD principle, the emerging field of Biodesign incorporates biological – living or once-living – systems into artefacts, harnessing their capacities to enhance experiential value and advocate regenerative goals (Karana et al., 2023). Within HCI, this biological contamination is gaining ground as “Biological HCI” or “Bio-HCI” (Pataranutaporn et al., 2018), achieving new narratives through novel functionalities, behaviours, and interactions (Zhou et al., 2022) and offering sustainable and circular scenarios to interfaces (Bell et al., 2025).

The wearable technology sector provides a particularly relevant context to explore these interdisciplinary evolution trajectories. Recent studies investigate the integration of biological systems to reduce the ecological impact of wearables, from substrate experimentation (Bell et al., 2023; Guridi et al., 2024; Lazaro Vasquez et al., 2023; Lazaro Vasquez & Vega, 2019b) to bio-electronic components (de Marzo et al., 2024; Lu & Lopes, 2022; Song & Paulos, 2023). These explorations – driven primarily by material properties – require methods, techniques, and tools spanning synthetic biology and biotechnology, design, and HCI, often combining biofabrication, digital fabrication, and craft practices (Camere & Karana, 2018; Ferraro et al., 2025; Pollini, 2024; Wu et al., 2023). While such interdisciplinarity opens promising avenues for circular futures in wearable design, the diversity of principles and practices also produces a fragmented framework, limiting the development of shared methodologies to guide designers toward circular innovation.

Addressing this gap, the study explores two research questions:

1. How can material-driven practices in Bio-HCI inform Circular Design pathways for wearables?
2. What replicable guidelines emerge from experimental and speculative material practices for circularity-led wearables?

To answer these questions, the authors present an annotated portfolio of empirical case studies that either operate within the wearable domain or offer methodological insights relevant to it, at the intersection of MDD and Bio-HCI. The paper elucidates how designers could mediate material knowledge across disciplines, integrating diverse and recurring methods, tools, and resources to realise circularity-led wearables. In doing so, the study contributes to the discourse on transitional materialities by emphasising the dynamic, meaningful, and transformative role of matter in shaping interactive artefacts such as wearable technologies. Lastly, it positions material-driven and speculative approaches as pathways that foster embodied, symbiotic interactions towards circular futures.

2. Theoretical background

Wearables operate at the intersection of the digital and physical spheres, functioning as interactive "portable infrastructures" that embed sensing, computation, and actuation (Ferraro, 2020). Their production draws on knowledge from an exceptionally broad range of domains, from medicine and biotechnology to textile and fashion design, interaction design, and ICTs (Gurova et al., 2020; Minaoglou et al., 2024). Their applications manifest in diverse artefacts, including flexible biosensors, electronic skins, soft robotics, smart jewellery, and textile-based antennas (Comotti et al., 2018; Kong et al., 2024; Marterer et al., 2024; McLellan et al., 2022; Romero-Perales et al., 2023; Song et al., 2022).

Despite this heterogeneity, the rapid proliferation and consumption of wearables raise unique growing environmental concerns, contributing to electronic waste (e-waste) (GlobalData, 2021; Timmins, 2009). Wearables contain diverse materials, ranging from hazardous substances (e.g., heavy metals) to precious metals (e.g., gold and silver) and low-value polymers that can degrade into microparticles, all of which can readily disperse into ecosystems. This complex, multi-material composition makes disassembly and component recovery extremely challenging (Horta Arduin et al., 2019; Robinson, 2009; Roy et al., 2022).

However, unlike other electronics, many wearables integrate electronic systems into fibres, further exacerbating recycling difficulties, as such structures impede effective material separation (Casciani & Wang, 2023; Guridi et al., 2024; Gurova et al., 2020; Timmins, 2009). Moreover, their high production volumes per each application, small size, and short lifespans imply that wearable technologies tend to generate more waste per unit and pose greater ecological risks than larger electronic appliances (Arbaud et al., 2024).

2.1 A Circular Design framework for a systemic response

The disposal challenges of wearables highlight the urgency of shifting from linear models toward more circular approaches. For this reason, broader e-waste management provides a useful framework for addressing the waste-intensive wearable sector.

Literature increasingly tackles the e-waste issue through Circular Economy (CE) strategies, including ecodesign, reuse, refurbishment, extended producer responsibility, material recovery via urban mining, reverse logistics, consumer disposal behaviours, and the use of lifecycle and material flow assessments to identify environmental hotspots and optimise supply loops (Erdiaw-Kwasie et al., 2024; Gaur et al., 2024; He et al., 2024; Thukral et al., 2023; Vieira et al., 2020; Xavier et al., 2021). As proposed in foundational visions, CE advocates the creation of separate but complementary closed loops, in which biological and technical resources remain distinct and retain their value through continuous circulation, rather than becoming waste (Ellen MacArthur Foundation, 2019; McDonough & Braungart, 2002). Complementing the *Butterfly Diagram*'s technical cycle (Ellen MacArthur Foundation, 2022), the 9R Circular Framework – Refuse (R0), Rethink (R1), Reduce (R2), Reuse (R3), Repair (R4), Refurbish (R5), Remanufacture (R6), Repurpose (R7), Recycle (R8) and Recover (R9) – offers practical guidance for enhancing material circularity across design stages (Potting et al., 2017). In this direction, also Human-Computer Interaction (HCI) can inspire the wearables sector with emerging systemic sub-disciplines as Sustainable Interaction Design (SID) (Blevis, 2007), Sustainable HCI (SHCI) (Remy & Huang, 2014), and especially Circular HCI (Vogel et al., 2020).

Collectively, these CE frameworks provide the conceptual foundation for Circular Design, guiding overarching design paradigms and concrete strategies for retaining material, technical, and ecological value (Geissdoerfer et al., 2017; Moreno et al., 2016). Applied to wearables, they inspire approaches that extend product lifespans, promote modularity, and foster ecological and material restoration across electronic systems (Ellen MacArthur Foundation, 2018; Gurova et al., 2020).

While these frameworks offer strategic guidance for closing material loops, their implementation ultimately depends on design practices capable of translating systemic principles into tangible, experiential artefacts.

2.2 From MDD to Bio-HCI

As shown by van der Velden and others (2015), focusing on material inputs across the entire lifecycle of wearable and textile-based smart products is among the most effective strategies to reduce their environmental footprint. Therefore, Material-Driven Design offers an exploratory framework to engage with the material complexities of wearable technologies.

As early as the 1980s, Manzini (1986) proposed his view of material, process, and product as an indivisible triad. He also anticipated today's convergence of materiality and information, where a new generation of "intelligent" artefacts not only occupy a physical space but also "flow in time".

Building on this lineage, the *Materials Experience* framework (Karana et al., 2013; Pedgley et al., 2021) expands the role of materials beyond technical performance toward aesthetic, emotional, and performative dimensions. Materials are conceived as mediators of meaning and identity, capable of evoking sensorial and affective responses (Karana et al., 2013) and carrying temporality to foster lasting relationships (Chapman, 2021). Through practices such as "material tinkering" and "DIY-Materials" approach (Parisi et al., 2017; Rognoli et al., 2015), designers can critically engage with matter, merging technical exploration and ecological reflection (Giaccardi & Karana, 2015; Karana et al., 2013).

The "material turn" in HCI reflects the same perspective, reframing interfaces as embodied, tangible and hybrid systems (Ishii & Ullmer, 1997; Ullmer & Ishii, 2000; Wiberg, 2018). Vallgårda and Redström (2007) expands these ideas through "computational composites", highlighting the expressive and behavioural properties of digital materials. Rooted in this framework, interaction design theory is increasingly characterising digital matter as "vibrant", "dynamic", and "agential", emphasising its active role in affecting human, technological, and ecological interactions (Barad, 2003; Bennett, 2010; Dade-Robertson et al., 2023; Parisi et al., 2018).

The integration of Biology and Biodesign principles into HCI – namely Bio-HCI – extends the traditional scope of this fertile area through a post-anthropocentric paradigm (Bell et al., 2025; Pataranutaporn et al., 2018). By incorporating living and once-living materials (such as fungi, algae, bacteria, and plants) into interactive systems, Bio-HCI reconceptualises interaction design as co-evolutionary rather than extractive (Zhou et al., 2022). Drawing on the shared goals of SID, SHCI, and Circular HCI, Bio-HCI advances frameworks grounded in ecological symbiosis and regenerative relationships (Blevis, 2007; Karana et al., 2023; Remy & Huang, 2014; Vogel et al., 2020).

Through the development of "living media interfaces" (Merritt et al., 2020) and "Designed Interactive Living Systems (DILS)" (Rognoli et al., 2025) – capable of sensing, reacting, and adapting to environmental stimuli – designers engage with biological materials to move toward multispecies and more-than-human perspectives. These systems can therefore arise biophilic aesthetics, biological sensing, circular alternatives, programmable functionalities, and novel forms of embodied interaction (Ferraro et al., 2025; Giaccardi, 2020; Karana et al., 2020).

For instance, studies in Bio-HCI demonstrate how biomaterials can seamlessly integrate with conventional electronics: Yao et al. (2015) employ living *Bacillus subtilis* natto cells as humidity-sensitive nanoactuators, Breed et al. (2024) and Barati et al. (2021) use bioluminescent microalgae to create dynamic, light-emitting interfaces, and Genç et al. (2022) leverage mycelium as a structural and interactive material. Instead, Song and Paulos (2023) explore biodegradable energy storage components, including graphite foils, activated charcoal electrodes, and carboxymethyl cellulose-based binders and electrolytes, pointing toward a future of decomposable, circular electronics. Other projects, such as those by Ofer et al. (2021) and Kuznetsov et al. (2018), illustrate how microorganisms – respectively, bioluminescent algae and bacteria with antibiotic substances – can be employed as co-creators in interactive, aesthetic, and ethical inquiry.

Within wearable design, Bio-HCI has enabled a new generation of biohybrid, biodegradable, and growable devices that rethink the relationship between technology, the body, and the environment. Emerging studies in the area have proposed notions as *Sustainable Interactive Textiles* (Guridi et al., 2024), *Dissolving Wearables* (Lazaro Vasquez et al., 2023), and, more broadly, *Wearable Bio-HCI* (Zhu et al., 2025), merging biological, digital, and material into speculative and experimental processes. Resulting research prototypes demonstrate how biodegradable materials and responsive substrates can support low-impact fabrication practices (de Marzo et al., 2024; Koelle et al., 2022; Zhu et al., 2024). *SCOBY Breastplate* (Bell et al., 2023) and other biomaterials-based ubiquitous computing projects (Lazaro Vasquez et al., 2022; Lazaro Vasquez & Vega, 2019a) exemplify "slow" ephemeral materialities, wherein the interface itself is aging, or dissolving over time. Meanwhile, projects like *Biohybrid Devices* (Nicolae et al., 2023) and the *Slime Mould Smartwatch* (Lu & Lopes, 2022) introduce notions of growth, decay, and care into wearable systems, blurring boundaries between maintenance, symbiosis, and interaction.

These explorations in wearable design require interdisciplinary methods ranging from materials science and laboratory research (Wu et al., 2023) to visual arts, textile design and

Biodesign (Camere & Karana, 2018). Through explorative techniques such as employing biofabrication, craft-based experimentation, digital fabrication, and DIY methodologies (Ferraro et al., 2025; Pollini, 2024), they reframe materials as lens of interaction, speculation, and actionable vision for circular responsibility. However, despite growing ecological awareness across design, HCI, and biological fields, the fragmentation of methods and disciplinary languages continues to hinder the development of shared frameworks for circular wearable innovation. As Bakker and Balkenende (2021) note, one of the major challenges lies in the lack of material literacy among designers, limiting collaboration with material scientists and industry.

Several emerging attempts are mapping biological materials according to their origin, properties, formats, fabrication processes, and applications (Guridi et al., 2024; Nicolae et al., 2023). Other scholars, such as Duarte et al. (2024), aim to classify case studies that demonstrate a concrete commitment to circular or sustainable approaches. Nevertheless, this area of investigation remains embryonic, characterised by ambiguous terminology, overlapping classifications, and a general lack of consensus on definitions. Additionally, Pollini and Rognoli (2021) emphasise the importance of LCA tools – typically outside the formal training of designers – for ecological impacts awareness of conventional and emerging materials. As a result, without structured collaborations with material scientists, biologists, and sustainability experts, the effective integration of such knowledge remains limited. Finally, another significant gap persists in employing biological materials into artefacts such as wearables, involving lack of standardisation norms and ethical concerns (Guridi et al., 2024; Kim et al., 2022).

As environmental pressures intensify, assessing issues of maturity, scalability, and circular potential of these materials becomes increasingly urgent. Integrating Material-Driven Design and Bio-HCI thus offers a holistic and interdisciplinary perspective in Circular Design to rethink wearables, positioning materials as transitional mediators between human, technological, and ecological systems.

3. Methodology

This study adopts a qualitative and exploratory approach, employing the annotated portfolio, a methodology rooted in HCI and design research communities (Gaver & Bowers, 2012). Rather than relying primarily on theoretical literature results, annotated portfolios position design practice itself as a mode of inquiry, where artefacts embody situated knowledge, tacit expertise, and critical insights. Through this approach, the analysis draws on a structured collection of real-world examples, revealing the material choices, methods, and values that inform experimental design practices.

In line with the present study's intent, this approach shows the potential to identify design principles and patterns aligning with circularity and emerging across Material-Driven Design and Bio-HCI, relating to the context of wearable and textile-based innovation.

3.1 Data collection and selection

The systematic mapping of case studies from MDD and Bio-HCI was carried out by encompassing projects directly situated in the wearable domain or offering methodological insights applicable to circularity-driven wearable innovation.

A total of 40 case studies was identified across academic research, open-source platforms, applied experimentation, and industry-led projects through scholar search engines, curated digital repositories, and social media profiles (see Appendix 1).

The selection process followed a rigorous procedure based on criteria including:

1. **Thematic relevance and consistency:** the project explicitly addresses material-driven creations;
2. **Origin within HCI and/or Biodesign**, with demonstrable impact on circularity, or innovation;
3. **Documentation quality and reliability**: academic publications, research reports, patents, industrial documentation, or conference proceedings, originating from universities, research laboratories, innovative companies, or startups in the analysed sectors;
4. **Methodological transparency**, ensuring clear articulation of materials, processes, methods, and outcomes.

As a preliminary step, each case study was numbered and systematised in *Excel* to map key attributes of each case and filter out those not relevant to the study's objectives. The refined corpus was then translated into an annotated portfolio using the interface design tool *Figma*, where each project was represented through a visual card featuring targeted annotations on (i) general information, (ii) typology of product with material focus, (iii) field of application, (iv) core components, manufacturing methods & techniques, employed tools, (v) Technology Readiness Level (TRL), (vi) implied circularity principles and (vii) intended design purpose (see Figure 1).

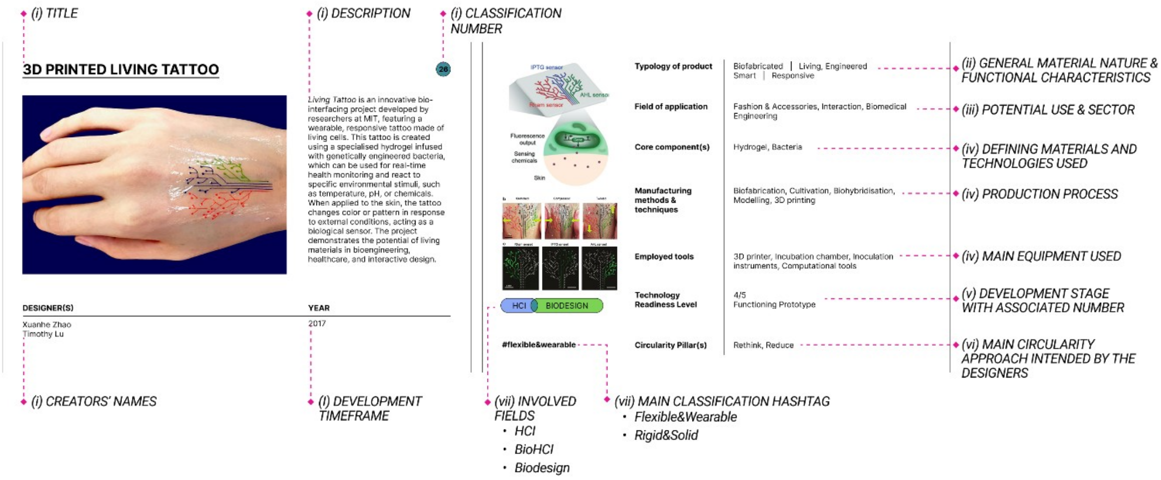


Figure 1 Example of visual card for each case study.

3.2 Categorisation and analytical frameworks

In a subsequent step, the “typology of product” category was expanded to include material-driven hierarchical subcategories, taking inspiration from classificatory approaches discussed in Rognoli and Ferraro (2021), Duarte et al. (2024), and Ferraro et al. (2025). This refinement allowed the materials to be distinguished according to their sustainable origin, level of “livingness,” or degree of “smartness”.

The subcategories were defined as follows, with the possibility of overlap between them:

- **Biobased** (natural, waste-based);
- **Biofabricated** (once-living, living, engineered);
- **Smart** (responsive, programmable, adaptive).

Each case study was examined using two complementary analytical frameworks that employed the categories of “Technology Readiness Level (TRL)” and “circularity principles”. The first framework assessed the artefacts' TRL, evaluating their technological maturity, feasibility, and potential for scalability beyond experimental contexts. This analysis enabled a structured comparison of projects at different stages of development, ranging from speculative prototypes to near-market applications.

The second framework applied the 9R Circular Framework (Potting et al., 2017) – Refuse (R0), Rethink (R1), Reduce (R2), Reuse (R3), Repair (R4), Refurbish (R5), Remanufacture (R6), Repurpose (R7), Recycle (R8) and Recover (R9) — to evaluate the capacity of each project to actively support Circular Economy strategies. Widely recognised in CE literature as an operational hierarchy of resource value retention strategies, the 9R framework provides a structured lens for assessing how design interventions contribute to reducing material extraction, extending product lifecycles, and minimising waste generation.

Combining TRL assessment with the 9R hierarchy integrates technological feasibility with systemic circular potential, offering a dual perspective on innovation maturity and environmental impact orientation.

4. Results

By cross-referencing the outcomes of the annotated portfolio, the study provided a comprehensive overview of design opportunities for manufacturing wearables.

Of the total 40 case studies, 12 intersect Biodesign and HCI within the emerging field of Bio-HCI and are considered foundational for inspiring wearable technologies. These cases – *Electric Skin, Living Mushtari, Bio Conductive Skin, E-seed, Living Things, Living Light, Rafigh, Myco-accessories, Slime Mould Smartwatch*, and *Biohybrid Device* – demonstrate already integrated biohybrid technologies and exemplify innovative possibilities in this domain.

Aiming to answer the two research questions, the analysis generated comparative insights and visualisations revealing broader patterns in circularity-led wearable design, from speculative explorations to market-oriented implementations (see Section 4.1 and 4.2). Drawing on the annotated findings (exemplified in Table 1), key circularity principles were identified and synthesised into a framework of design pathways (Section 4.3 and 4.4), providing systematic guidance for designers seeking wearable alternatives that actively support circular practices.

4.1 Emerging design patterns

The analysis of the collected projects firstly quantified the occurrence of the three dominant material-driven product typologies, acknowledging overlap among categories.

The first and most prevalent cluster (approximately 60%) is **biofabricated materials and systems**: 40% of the cases rely on fully living substrates (such as *Physarum* slime mould, microalgae, bacteria, plants); 25% employ once-living materials (e.g., grown and stabilised bacterial cellulose and mycelium); and around 10% involve engineered biological systems developed through synthetic biology (i.e., hydrogels). This distribution highlights a leading emphasis on experimental, bioderived matter, often explored as speculative prototypes. The second cluster concerns **smart materials**, representing about 35% of the corpus. These projects – ranging from LCE-based actuators to 4D fibres or biologically integrated sensor – demonstrate a growing interest in novel material-driven solutions for HCI and a consolidation of the biodigital interfaces trajectory within the field. Finally, the third cluster consists of **biobased materials** derived from natural or waste sources (such as clay residues, sawdust, gelatine, or recycled textiles), constituting 25% of the dataset.

The subsequent focus on the recurrent manufacturing methods reflected a dual dependence on biological cultivation and digital fabrication. **Biofabrication and growth-based processes,** appearing in the 60% of the projects, frequently include incubation, inoculation, and extended care procedures integral to the design. **Digital fabrication techniques** are present in about half of the portfolio, ranging from rigid and flexible 3D printing to parametric modelling and morphological growth algorithms. **Textile-based methods**, including knitting, weaving, embroidery and moulding, appear in about 30% of cases, while **programming and electronics integration** emerge in roughly 40%. This methodological coexistence, in line with the materials considerations, indicates that practitioners currently operate across experimental biology and advanced prototyping infrastructures for circularity in HCI.

The tools employed across the projects further characterise these patterns. **Wet-lab equipment** such as incubation chambers, inoculation tools, Petri dishes, and growth media signals the prevalence of early-stage interdisciplinary experimentation. **Digital fabrication equipment** – including 3D printers, parametric modelling tools, and machine-knitting systems – often supports the creation of scaffolds or hybrid structures. **Electronics and HCI toolkits**, typically based on microcontrollers and sensor-actuator systems, are concentrated in programmable wearables, while **DIY and craft tools** appear most frequently in biobased and low-tech explorations.

4.2 TRLs

The evaluation of Technology Readiness Levels confirmed the strongly experimental nature of the domain. Approximately 70% of the projects fall within TRL 1 to 4, indicating **speculative concepts, exploratory experiments, or early functioning prototypes**. Around 25% reach TRL 5 to 7, representing **verified or qualified prototypes** such as *BioGarmentry*, *Alganyl*, or *Living Light*. Roughly 5% of the dataset, including *MuSkin*, *H.O.R.T.U.S. XL*, and the *Genesis Eco Screen*, represent near-market applications, **approaching full development** (TRL

8–9) yet still remaining just below the highest maturity tier. This distribution illustrates a pronounced gap between material experimentation and commercial implementation, particularly for living or engineered biological systems.

4.3 Circularity principles

The examination of circularity strategies, interpreted through the 9R Framework, shows that **the most frequent orientations are Rethink (R1) and Reduce (R2),** reflected in biohybrid interactions, biodegradability, and restorative material approaches. Reuse (R3), Repurpose (R7) and Recycle (R8) appear sporadically, mainly in textile and other upcycling contexts. Refuse-, Repair-, Refurbish- and Remanufacture-oriented strategies (R0, R4, R5, R6) are largely absent, while specific projects engage in Recover (R9) processes, involving microbial energy or photosynthetic activity.

Overall, these results show that these representative case studies currently lean toward models supporting smarter life cycle optimisation and reconfiguring conventional manufacturing notions (R1–R3) as well as strategies focused on material reuse and recovery at end-of-life (R7–R9) (Potting et al., 2017).

Table 1 3 illustrative examples of case study annotations results.

Project Title & Designer(s)	**Typology of Product & Main Materials**	**Manufacturing Methods & Tools**	**TRL**	**Circularity Principles**
Electric Skin *Nada Elkharashi, Catherine Euale, Sequoia Fischer, Paige Perillat-Piratoine*	Bioenergy membrane: *Geobacter Sulfurreducens* (bacteria)	Wet-lab cultivation; laser cutting; integration of conductive paths	4	Rethink (R1), Reduce (R2), Recover (R9)
Living Mushtari *Neri Oxman, Christoph Bader, Dominik Kolb, Will Patrick, Sunanda Sharma, Steven Keating*	Engineered living wearable: Cyanobacteria + Microalgae	Multi-material 3D printing; parametric design; wet-lab cultivation	2–3	Rethink (R1), Reduce (R2), Recover (R9)
Sakuu 3D Printed Batteries *Sakuu*	Smart batteries: Additively manufactured solid-state materials	Multi-material 3D printing (functional inks); advanced fabrication	5–6	Reduce (R2), Repurpose (R7), Rethink (R1)

4.4 Mapping Circular Design pathways

The previous section indicated that circularity principles do not emerge as isolated considerations but are deeply entangled with material selection, fabrication techniques, and tool choices. To address the research questions, the authors translated the design patterns and circular pathways into a transferable design framework for circularity-led wearable manufacturing in which the entry point is not the material nor the fabrication technology, but the circularity principle itself.

Four overarching pathways became particularly evident in connecting the design patterns with circularity strategies. R0 was not considered as a pathway in this framework, as *refusing* the use of a product altogether represents a foundational principle of circularity, annihilating resource extraction, material production, and waste generation (Potting et al., 2017).

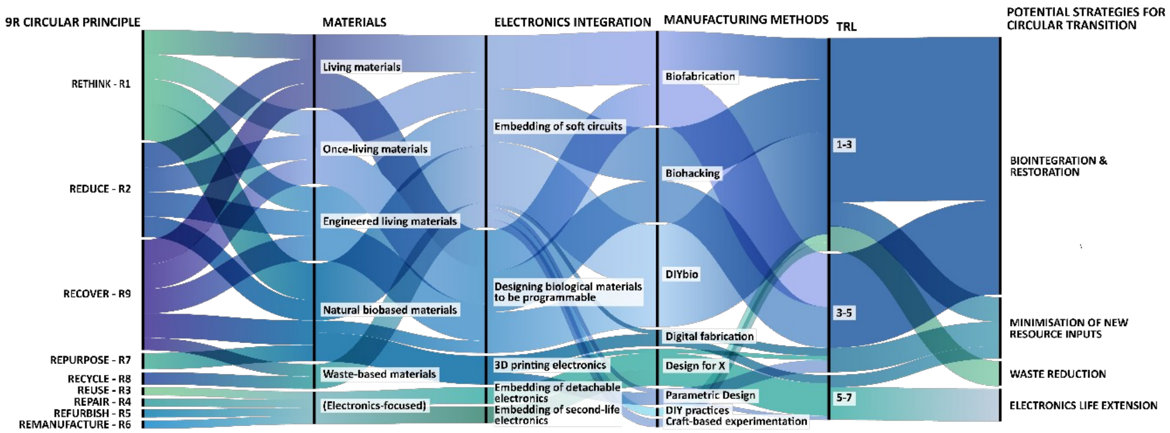
The resulting domains represent distinct yet interconnected modes of operationalising circularity:

1. **Rethink (R1), Reduce (R2), Recover (R9) → Biointegrated & Restorative Strategies**
   This pathway aligns with biofabrication and biohacking practices, where designers work with living, once-living, engineered and biobased biological systems (e.g., mycelium, bacterial cellulose, algae, moulds, and biopolymers), suggesting an intrinsic alignment with biointegrated and restorative approaches that extend circular strategies beyond conventional recycling. Fabrication typically relies on wet-lab procedures – including inoculation, incubation, and cultivation – often combined with moulding or growth-based shaping. In the absence of interdisciplinary collaboration, many of these projects rely on low-tech or DIY-bio toolkits. Wearables' circularity is enacted through biologically enabled and restorative logics, either by integrating biological components into electronic systems or by designing biological materials that become functional soft electronics themselves (e.g., smart programmable matter).
2. **Rethink (R1), Reduce (R2), Repurpose (R7) → Minimisation of New Inputs Strategies**
   In this domain, digital fabrication, parametric design, and Design for X strategies enable designers to work with natural or biobased materials while adopting efficient geometrical and modular logics, or computationally optimised patterns. Techniques such as multi-material 3D printing, robotic deposition, generative modelling, and machine knitting primarily facilitate novel ways of shaping form and function, enabling on-demand production, and reducing the inputs and inefficiencies associated with subtractive processes. In wearable design, these approaches leverage advanced digital tools and strategic design decisions to lower primary resource consumption while seamlessly integrating electronic components.
3. **Recycle (R8), Recover (R9) → Waste Reduction Strategies**
   DIYbio, DIY making, and textile-based craft practices form this third domain,

including material-making toolkits, open-source electronics platforms such as Arduino, manual moulding and casting techniques, and home-lab protocols. These practices enhance wearables' circularity by simplifying production, reducing waste, and enabling the recycling of textile and food by-products into new materials. They also support local, decentralised, community-driven models of making that challenge conventional industrial distribution. Often combined with low-cost or open-source electronic components, these approaches facilitate accessible, resource-efficient experimentation while scaling circularity through participatory infrastructures.

4. **Reuse (R3), Repair (R4), Refurbish (R5), Remanufacture (R6) → Electronics Life Extension Strategies**

   This domain addresses lifecycle management of electronic components, like sensing modules, microcontrollers, PCBs, and conductive pathways, rather than biofabricated or biobased substrates. Strategies focus on extending functional lifespan, reducing the need for new materials, and supporting sustainable electronics management. Practical implementations include modular electronics design that allows individual components to be replaced or upgraded without discarding the entire device, standardised connectors to facilitate repair, and maintenance-friendly anatomies that simplify troubleshooting and refurbishment. Remanufacturing may recover functional circuits or reprocess



   components for new devices, creating closed-loop material flows. By embedding these strategies, wearable design can balance technological innovation with circularity while complementing restorative and minimal-input approaches in biohybrid and digitally fabricated systems.

These four domains have been subsequently reorganised into a visual structure (Figure 2), illustrating how each circularity principle cascades into materials and electronics integration, fabrication approaches, TRLs and specific strategies.

Figure 2 Design framework showing the Circular Design pathways for wearable design. Credits: Authors

5. Discussion and conclusions

As wearable technologies become increasingly adopted, their environmental impact grows, making it critical for designers to understand what manufacturing choices can promote circularity.

Emerging wearable alternatives position materials as central actors, yet their potential to drive circular practices remains underexplored. Material-driven interdisciplinary approaches – intersecting biology, design and HCI – demonstrate how materials can serve as lenses for interaction, experimentation, and ecological innovation. However, fragmented methods and gaps in material literacy and LCA competence (Bakker & Balkenende, 2021; Pollini & Rognoli, 2021) – together with ethical and regulatory issues in involving biological materials in artefacts (Guridi et al., 2024; Kim et al., 2022) – still obstruct advancement.

Through an annotated portfolio, the study mapped 40 case studies from Material-Driven Design and Bio-HCI, encompassing projects directly situated in the wearable domain or offering methodological insights applicable to circularity-led wearable innovation. The analysis revealed broader design patterns in the interested area, including recurrent choices in materials, fabrication techniques and tools, level of technological maturity and key circularity principles.

Three cross-cutting insights emerge from these patterns.

1. **Materials are the main driver of innovation in circular wearables.** Findings showed that material typology significantly shapes manufacturing routes, circularity strategies and achievable levels of technological maturity. In this scenario, the iterative, exploratory nature of MDD enables designers to prototype biointegrated or restorative solutions, offering replicable guidelines for working with emerging materials and hybrid fabrication ecosystems.
2. **Bio-HCI is a fertile context for ecological and embodied interactions in wearable design.** The hybridisation behind the analysed case studies expands the repertoire of MDD within Bio-HCI, positioning materials not as passive carriers for technologies but as operative mediators that actively shape interaction modalities and circular outcomes. Biological materials enable forms of innovation and exploration that remain inaccessible within the constraints of traditional HCI and wearable design. Through these entanglements, designers probe transitional materialities that enable embodied, symbiotic behaviours grounded in care, decay, and growth, where material acts as both interface and design driver.
3. **DIY and speculative practices are driving circular transition for wearables.** The study demonstrated a marked shift in design and HCI toward biofabricated, biobased, and biohybrid substrates, such as mycelium composites, bacterial cellulose, and engineered living systems. These materials predominantly occupy low Technology Readiness Levels (TRL 1-4), underscoring both their transformative potential and their experimental fragility. Only a small number of cases reach higher TRL positions (TRL 5-7), confirming a persistent gap between

exploratory prototyping and commercially scalable solutions. This underscores the need for translational strategies to bridge research and practical circular implementation. MDD practices, such as material tinkering, DIY approaches and the generation of speculative scenarios, play a crucial role in shifting designers' mindsets, representing foundational steps toward market-ready solutions.

Building on these implications, the combined analysis of the material typology, manufacturing methods, 9R framework and TRL classification provided a practical contribution for designers in the wearable domain.

Identifying circular pathways and supporting replicable practices across disciplines offers several key benefits. First, it translates abstract circularity concepts into concrete, actionable design decisions, linking each principle to specific materials, fabrication techniques, tools, and potential strategies for circular transitions. For example, starting with *reducing* could inspire design strategies that employ biological organisms as programmable smart components, generating self-sustaining devices and enabling restorative scenarios. In contrast, beginning with *repairing* emphasises wearables with detachable electronic components that can be easily accessed, repaired, and replaced. Thereby, this framework helps designers navigate the complex intersections of Circular Design, MDD, and Bio-HCI within the wearable domain.

Second, it provides a shared language for interdisciplinary teams of designers, material scientists, biologists and engineers to navigate heterogeneous material logics and anticipate trade-offs. Third, by foregrounding the life cycle from the outset, the framework embeds circularity in the earliest conceptual stages, encouraging designers to critically question or even refuse the creation of unnecessary wearables.

While this initial mapping establishes clear connections between circularity principles and designers' choices, further developments could introduce more granular strategies for Circular Design. Such an extension would better connect systemic models with the practical realities of biofabrication, textile engineering, soft electronics, and digital manufacturing.

Conceptually, the present study supports a shift from viewing materials in wearable technologies as passive substrates to understanding them as active agents that shape functionality, human-technology relations, and ecological systems.

Taken together, the research outcomes point toward circular futures for wearable design, where material experimentation, environmental awareness, and biobased adaptive interfaces converge into embodied, symbiotic interactions and foster responsible behaviours.

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About the Authors:

Nicla Guarino is a Ph.D. student at the Design Department of Politecnico di Milano, working in the fields of fashion and wearable design. Her research explores circular design solutions to textile and electronic waste through interdisciplinary, material-driven, and biodesign approaches.

Venere Ferraro is Associate Professor of Interaction Design at Politecnico di Milano. Her research focuses on interaction design, data physicalization, wearable technologies, and living artefacts, exploring how emerging materials and data shape new forms of embodied and tangible interaction.

Valentina Rognoli is Associate Professor of Design at Politecnico di Milano, focusing on materials design, biodesign, and regenerative approaches. She directs the *Materials Design for Transition* group and *B.Lab*, investigating living systems and multispecies perspectives in design research and education.

Appendix 1 *Comprehensive list of all case studies included in the analysis.*

#	Project Title & Source	**Designer(s)**	**Short Description**
1	FibeRobo mit/fiberobo	Jack Forman, Ozgun Kilic Afsar, Sarah Nicita, Rosalie Hsin-Ju Lin, Liu Yang, Megan Hofmann, Akshay Kothakonda, Zac Gordon, Cedric Honnet, Kris Dorsey, Neil Gershenfeld, Hiroshi Ishii	Shape-shifting fibre enabling morphing textiles through thermal activation
2	MuSkin gzespace/muskin	Zero Grado Espace	Mycelium-based vegan leather alternative to animal hide
3	Electric Skin electricskin.org	Nada Elkharashi, Catherine Euale, Sequoia Fischer, Paige Perillat-Piratoine	Renewable bacterial energy sources for wearables and bioelectronics
4	Project PrimRose adobe/project-primrose	Christine Dierk, TJ Rhodes, Gavin Miller	Interactive digital dress featuring programmable color and pattern changes
5	Bio-textiles installation naturalmaterial/frama	Natural Material Studio, FRAMA CPH	Soft bio-textiles produced from seaweed and Spirulina algae, clay pigments, collagen binders and air-bubble-infused foam
6	Low-cost Flexible Wearables wyss.harvard.edu	Wyss Institute Research team	3D-printed stretchable sensors for soft, low-cost wearable systems
7	Cambio de Piel sofiaguridi.xyz/skin	Sofia Guridi	Material exploration integrating biomaterials into textiles for biodegradability
8	Wearable Systems Lab sofiaguridi.xyz/wsl	Sofia Guridi	Wearable device supporting post-stroke rehabilitation

#	Project Title & Source	**Designer(s)**	**Short Description**
			through biofeedback
9	Biogarmentry dezeen/biogarmentry	Roya Aghighi	Living photosynthetic garments incorporating algae for CO_2 absorption
10	Gunya MYC_Couture 04 rootsfoundation.nl	Dasha Tsapenko	Fashion piece made of raw hemp and sawdust bonded with mycelium
11	Mycelium Block umprum/myceelab	Myceelab (UMPRUM Prague)	Robotic-based 3D printed mycelium blocks
12	Pulp-based Computing 10.1145/1520340.1520525	Marcelo Coelho	Paper-based computing using conductive ink and smart materials
13	Living Mushtari mit/living-mushtari	Neri Oxman, Christoph Bader, Dominik Kolb, Will Patrick, Sunanda Sharma, Steven Keating	3D-printed wearable hosting engineered microorganisms for symbiotic functions
14	Bio Conductive Skin flickr/giuliatomasello	Giulia Tomasello	Conductive bacterial cellulose as a bioelectronic wearable interface
15	HeartBeatDress heartbeatdress	Anouk Wipprecht	3D-printed interactive fashion garment that responds to biometric data
16	Microbes Make Mountains microbi.xyz/mountains	Laura Maria Gonzalez	Microbial 3D printing for sustainable, self-regenerating bio-cementation
17	Possible Tomorrows yg/possible-tomorrows	Ying Gao	Robotic garments that react to proximity and movement
18	Caress of the Gaze caress-of-the-gaze	Behnaz Farahi	3D-printed wearable responding to the gaze of

#	Project Title & Source	**Designer(s)**	**Short Description**
			onlookers
19	Medically Prescribed Jewellery olganoronha/mpj	Olga Noronha	Jewelry functioning as medical sensors and therapeutic device
20	beGROUNDED l.campos/begrounded	Lara Campos	Wool-based garments grown from chia seeds integrating living systems into textiles
21	Textile Upcycling ig/textileupcycle	Cara Huato	Bioplastic materials incorporating recycled textile fibers for upcycling
22	SCOBY Breastplate fb/scoby-breastplate	Fiona Bell, Derrek Chow, Hyelin Choi, Mirela Alistar	Kombucha-based wearable integrating LEDs and living cellulose.
23	Self-Cleaning Textiles fb/self-cleaning-textiles	Fiona Bell, Alice Hong, Andreea Danielescu, Aditi Maheshwarir, Ben Greenspan, Hiroshi Ishii, Laura Devendorf, Mirela Alistar	Bio-reactive textiles with self-cleaning microbial layers
24	Alganyl fb/alganyl	Fiona Bell, Ella McQuaid, Latifa Al-Naimi, Mirela Alistar	Customisable biomaterial derived from algae for textile applications
25	Vespers III mit/vespers-iii	Neri Oxman, Christoph Bader, Sunanda Sharma, Rachel Smith, James Weaver	Biofabricated masks hosting bacteria that produce pigments when exposed to chemicals
26	Living Tattoo mit/3d-living-tattoo	Xuanhe Zhao, Timothy Lu	3D-printed bacterial hydrogel tattoo capable of environmental sensing
27	GENESIS Eco Screen bigrep/genesis	BigRep	3D-printed architectural screen supporting plant growth and

#	Project Title & Source	**Designer(s)**	**Short Description**
			water circulation
28	H.O.R.T.U.S. XL ecologicstudio/hortus	ecoLogic Studio	Large-scale bio-sculpture receptive to human and microbial life, containing microalgae and functioning as a photosynthetic bioreactor
29	E-seed ivanhenrique/eseed	Ivan Henriques	Bio-hybrid, self-sustaining robots able to identify optimal locations to implant seeds for reforestation and ecological restoration
30	Living Things livingthings	Jacob Douenias, Ethan Frier, Lena Tesone	Interior lighting system powered by photosynthetic microalgae
31	Rafigh foadhamidi/rafigh	Foad Hamidi, Melanie Baljko	Interactive display using mushroom growth to support speech language intervention for children with disabilities
32	Living Light novainnova/ll	Nova Innova	Lamp powered by microbial fuel cells integrated with plants
33	3D Print Batteries sakuu/batteries	Sakuu	3D-printed solid-state batteries for sustainable electronics
34	Carbon Eaters orkantelhan/carbon-eaters	PUMA, Orkan Telhan (MIT Design Lab)	Color-changing stickers with microbial activation indicating air quality
35	Myco-accessories elv/myco-accessories	Eldy Lazaro Vasquez, Katia Vega	Mycelium-based wearable accessories exploring biodegradability and sustainaibility
36	FloraWear	Hye Yeon Nam, JaNiece Campbell, Andrew M.	Wearable integrating living plants for aesthetic and

#	Project Title & Source	**Designer(s)**	**Short Description**
	hynam/florawear	Webb, Brendan Harmon	symbiotic interaction
37	Slime Mould Smartwatch 10.1145/3526113.3545629	Jasmine Lu, Pedro Lopes	Biohybrid smartwatch using slime mould for living sensing and care-based interaction
38	BioVer thoraha/biover	Thora H Arnardottir, Jessica Dias, Nikos Argyros, Agustina Ros	Wearable device supporting biofeedback and biophilic interaction
39	INTERFERENCE v-labelle/interference	Viviane Labelle	Interactive textile with stimulating effects through cross-polarized filters
40	BioHybrid Device - Game Controller biohybrid-device	Madalina Nicolae, Marc Teyssier, Vivien Roussel	Biohybrid device in the shape of a game controller merging bacterial cellulose with digital interfaces