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Healing Materialities: framing Biodesign's potential for conventional and regenerative sustainability

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Abstract

The rediscovered potential of 'growing' instead of 'making' drives the emergence of new materialities. This is leading to innovative developments in biotechnologies and Biodesign, both of which are intricately connected and seen as transformative elements in the discourse on sustainability. Biofabricated materials are starting to be evaluated using established sustainability metrics such as life cycle assessment, highlighting their essential role in the circular economy and shedding light on some overlooked process-dependent environmental burdens. At the same time, some biodesigned materials and artefacts are characterised by their ability to transcend the conventional concept of sustainability, embracing the principles of Regenerative Design thanks to the restorative and regenerative potential of living and bioreceptive materials. The study explores the main Biodesign variables, presenting a taxonomy created to comprehensively understand the phenomenon. The resulting findings highlighted the dual nature of Biodesign, which promotes both inner and outer sustainability. These findings gave rise to a conceptual framework defined as 'Healing Materialities', developed by the authors to highlight the main Biodesign variables discussed while addressing a broad spectrum of ecological potentials, from conventional to regenerative sustainability. The article discusses the concept of 'Healing Materialities', emphasising the role of Biodesign in supporting a profound ecological turn and advocating the adoption of regenerative materials and processes capable of harmonising the long-term needs of both human and non-human entities.

Introduction

Biodesign is a transdisciplinary approach bridging design and science in order to create innovative materials, products and systems. The aim is to harness bio-based building block materials, living organisms and biological processes with the precise purpose of leveraing their inherent capabilities to generate and manufacture materials, products and biotechnologies.

The main objective of this study is thus to grasp a picture of the rapidly evolving phenomenon of Biodesign. Materials obtained from biological processes, such as biomanufacturing, have been considered through a few early studies addressing conventional sustainability metrics (e.g. life cycle assessment (LCA)), emphasising their crucial role in the circular economy but also highlighting some overlooked process-dependent environmental burdens. In parallel, other Biodesign projects hardly fit in such metrics, despite standing out for the possibility of overcoming the concept of sustainability as currently intended, thanks to restorative and regenerative features typical of living and bioreceptive materials.

Case studies in Biodesign can encompass a broad spectrum of variables. Simply referring to the materials and artefacts produced by living organisms, different species may be involved (mycelium, algae, bacteria, enzymes, yeasts, plants, insects), undergoing different processes (3D printing, moulding, breeding), through high- or low-tech solutions (e.g. from bioreactors to hand modelling), based on different life stages of the organisms (from being kept alive to stabilised materials), with different approaches (from speculative to feasible). In summary, the field of Biodesign offers a rich tapestry of possibilities, where a wide array of variables converge to generate innovative and sustainable solutions.

The article discusses the main Biodesign variables able to support an ecological turn, presenting a taxonomy developed to grasp the phenomenon in its entirety. Analysing the wide range of Biodesign case studies[1] through this taxonomy highlighted how the organisms' degree of livingness and participation in the design process could result in a broad spectrum of ecological potentials, from conventional to regenerative sustainability. These main findings led to the conceptual framework of *Healing Materialities*, aiming to clarify the dual nature of Biodesign, pushing both inner and outer sustainability through practical and speculative approaches as well as material outcomes.

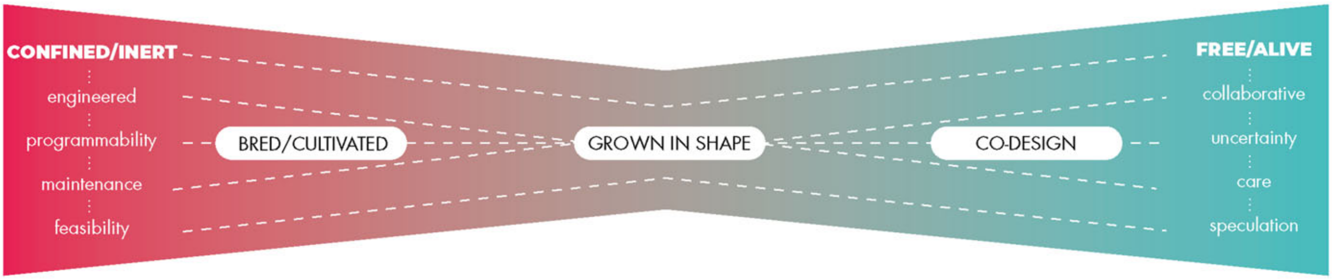

Figure 1. Biodesign taxonomic scale (Pollini, 2021, readapted in 2023).

A taxonomic scale framing the two driving forces behind Biodesign for sustainability

The field of Biodesign is relatively young and rapidly evolving; as such, scholars and researchers have been actively working on taxonomies and categorisations to better understand and frame its different facets. These efforts aim to provide a structured framework for analysing and classifying the various aspects of Biodesign (Camere & Karana, 2017; Carol, 2013; Esat & Ahmed-Kristensen, 2018; Lantada et al., 2021; Rognoli et al., 2022; Zhou et al., 2021).

The taxonomy proposed here[2] aims to complement these previous studies by providing a comprehensive overview of the Biodesign phenomenon. In fact, it focuses on understanding the multifaceted nature of the field by observing recursive patterns in Biodesign case studies and aims in parallel with their analysis through an exploratory and broader approach based on three main factors:

Organism involvement: This factor assesses how deeply the organism is integrated into the design process. It considers whether the organism plays a central role in shaping the final design outcome or if it is a merely passive component.

Human/non-human interaction: This factor examines the degree of interaction and relational connection between the user/designer and the organism. This aspect defines whether there is a close, collaborative relationship or a more detached, directive one.

Predictability of results: This factor explores the degree to which the design outcomes are predictable, following linear processes or non-linear and less predictable ones, often influenced by the inherent characteristics and abilities of the living organism involved.

The main patterns observed in Biodesign's case studies, which relate to two predominant driving forces visualised in divergent poles of significance, are shown in Figure 1.

The taxonomy presented here captures the multifaceted nature of Biodesign by mainly considering the role played by the organism involved. This diagram can serve as a valuable tool for researchers and Biodesign practitioners; it provides a broader perspective that considers the diversity and complexity of Biodesign projects, highlighting two fundamental driving forces within Biodesign, which can further help understanding the dynamics of the field and potential directions for future research and innovation.

Given the biological origin of biodesigned materials and artefacts, a fundamental aspect emphasised by the developed taxonomic scale is the management of organisms in the design process. Recognising that dualism can be misleading in promoting progress and social values (Jones, 2009), the one at the basis of this taxonomy is derived from the organism's fundamental condition: on the one hand, it is alive and free to express itself; on the other, it is instead restricted or limited (either because of its death or by the lack of its free expression). This on/off organisms' expressivity determines design processes and outcomes based on a variety of divergent design possibilities, affecting values, philosophical and ethical concepts and organisms, designers and users' experiences.

The taxonomy proposed articulates between two extremities, further defined by opposed sub-features:

1. (Organism) Confined/inert

When a biomanufactured product wants to achieve industrial scalability, in most cases, the organisms are confined by a given space, time and function. Here, organisms are engineered and carefully directed during their growth phase, often stabilised at the end of the growth process for subsequent use; they have been programmed to yield highly predictable outcomes, for example, in making materials or serving a precise function connected to their aliveness. In this polarity, materials exhibit inertia as they lack vital expressiveness (by confinement or stabilisation processes, the latter usually resulting in the death of the organisms). This part of the scale defines projects where designers and biotechnologists predefine scales and shapes, leaving minimal decision-making to the organism. Still, they must deal with non-linearity, considered in biology as a characteristic of complex biological regulatory networks (Manicka et al., 2022). This makes the programmability of biotechnology face new challenges and continuous progress in controlling standardised outcomes. During the growth phase, strategies can be applied to guide the desired final form (e.g. mechanical constraints) or widen the available material qualities (e.g. densification and material composition strategies) (Wang et al., 2024; Rigobello and Ayres, 2023). Consequently, the organism's influence on the final performance or aesthetics of the object/materials is not significant from this perspective. As these biotechnologies approach scalability, the necessity for programmability often leads to a more standardised aesthetic.

It's easy to imagine that the confinement of the organisms and their number in a process of scaled biofabrication influences the human/non-human relationship, too. To our knowledge, there are no studies on this topic yet; however, it may help to draw a parallel with comparative psychology, where the study of human–animal interactions highlights how companion animal literature tends to refer to human–animal 'bonds', but the interaction with laboratory or farm animals is addressed by the specific literature as 'relationship' (Hosey & Melfi, 2014). If humans can express ambiguous and ubiquitous behaviours with other animals, shifting from friendship to exploitation (Maréchal & Zee, 2024), this might also be the case with other non-human entities. Furthermore, it seems plausible to think that in large-scale biotechnological facilities, the high number of living beings within a production site necessitates maintenance (such as optimal temperature and humidity conditions) based on automation and functionality,

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which can limit the potential for a close and emotionally charged relationship with the organisms involved.

In this part of the scale, we find startups and companies with strong investments in research and development whose aim is the feasibility and scalability of biotechnological productions (Lee et al., 2020). To make an example from one of the most tested organisms, the mycelium, we find in the literature feasibility studies in various specific sectors, from architecture (Almpani-Lekka et al., 2021) to animal leather substitute (Amobonye et al., 2023) and advanced functional materials (Elsacker et al., 2023).

Feasibility, engineering and predictability also facilitate conventional sustainability studies of products and materials related to this part of the scale. Results from early LCAs in this field will be thoroughly investigated in a folowing paragraph dedicated to biomanufactured materials for conventional sustainability.

2. (Organism) Free/alive

The right extremity of the scale refers to those Biodesign case studies in which the organisms are maintained in a state of vitality, engaging in a collaborative co-design process driven by mutual interests. This polarity encompasses organisms and living materials that undergo changes, mutations and evolution throughout their life cycles. They freely express themselves in response to internal and external stimuli and while being influenced by the perceived environment. Biodesigners often perceive the organism's agency, acknowledging their act of co-design; this also triggers feelings of care, affecting the perception and relationship with the organisms while designing (Camere & Karana, 2018). If the organisms are left alive and free to express, as a consequence of the transitory nature of lifewe might also address open-ended design, described as an unfinished process where the final outcome of the project is left open and flexible (Ostuzzi, 2017; Vuylsteke et al., 2022) – and therefore, in this case, also ready to be explored by non-human agencies. Here, the vitality and agency of the organisms become a desired and functional variable for design purposes (Karana et al., 2020). While 'programmability' aligns with the industry's demand for scaled-up processes, it is 'uncertainty' that characterises processes that guarantee the organism a high degree of freedom and expression. A living aesthetic is an aesthetic of change, following the life stages of the organism and its responsiveness to the environment; this translates into imperfection and non-homogeneity of the final piece. The imperfect and transitory nature of Biodesign brings novelty on a material, aesthetical, sensorial and ethical level, leading to new material experiences (Karana et al., 2013; Pedgley et al., 2021). This polarity highlights how aesthetic values within Biodesign could capture the vitality of organisms and even contribute to the narrative of the very object/material (Pollini & Angelini, 2021).

Design students have reported an emotional bond in free experimentations with living organisms such as mycelium and bacterial cellulose (Hirscher and Posch, 2023). Moreover, small-scale experimental productions still maintain an intimate connection with the materials and organisms. These processes often involve meticulous daily observation and sense of genuine care that can nurture feelings of affection, fostering empathy and leading to a deeper understanding of the organism (Kim et al., 2022). Exposing users to co-exist with unconventional living organisms pushes to relate to non-humans in unusual ways, acknowledging their presence, needs and beneficial activity towards our existence. This emotional connection helps increase awareness of how we perceive other living beings; in fact, within the Biodesign discourse, human–non-human interactions are often the basis of highly debated concepts, such as more-than-human (Tsing, 2013; Wakkary, 2021; Camocini & Vergani, 2021) and multispecies design (Gatto & McCardle, 2019; Keune, 2021; Veselova & Gaziulusoy, 2021).

Compared to the previously described extremity, in this part of the scale, we often find projects that take a more experimental and speculative approach to generate proof of concept or stimulate questions and critical thinking. A strong speculative element enhanced the fascination surrounding the emergence of the Biodesign approach (Ginsberg et al., 2017; Myers, 2012). Consequently, the final diptych of the taxonomical scale embraces both feasible and speculative approaches, tracking the different natures of Biodesign projects. There is another category of projects in this part of the scale which is related to biodiversity enhancement and/or bioremediation activities. In this case, organisms are often supported by materials or surfaces/structures that can welcome them and make them thrive - such as bioreceptive materials, which will be explored in depth in the next paragraph.

Bioreceptive design: the role of life-enabling materials in Biodesign

Bioreceptive materials play an important role within Biodesign, supporting living organisms often placed on the right side of the scale. Bioreceptivity is a crucial material feature that enhances biotic and abiotic relationships. It was defined in 1995 by Guillitte as 'the aptitude of a material (or any other inanimate object) to be colonised by one or several groups of living organisms without necessarily undergoing any biodeterioration' (Guillitte, 1995). The concept of Bioreceptive Design (BD) (Cruz & Beckett, 2016) has been expanded by the authors with a focus on Material Design (Pollini & Rognoli, 2021), highlighting how, in the field of Biodesign, the colonisation of surfaces by living organisms can be a deliberate condition that serves a design purpose. Bioreceptive design can be defined as the intentional design of material features that foster life's flourishing on material surfaces; in fact, 'colors, porosity, and shape, among other features, can be designed to meet the requirements of organisms to thrive, thus promoting inert-living assemblages with distinct design and environmental purposes' (Pollini & Rognoli, 2021). Bioreceptive materials can also be addressed as '*life-enabling materials*', stimulating biological colonisation and multispecies design (Ibid.). As for Biodesign, the nature of the projects in BD can change drastically from speculative to feasible: the attraction of life forms can be used as a key element to stimulate critical thinking (although the requirement for the organism's survival makes the projects quite feasible), nevertheless most BD projects seek effective biodiversity enhancement (Ibid.). Here, key aspects are multispecies design, bioremediation abilities and the aim for greater integration of natural elements into the human built environments. In these cases, designed bioreceptivity has the potential to support nature-based solution, defined as solutions that involve working with and enhancing nature to help address societal challenges (Seddon et al., 2020); in fact, many colonised artefacts can provide low-maintenance systems for biodiversity, heat and pollution mitigation in different areas. Bioreceptive materials possess remarkable potential, encompassing areas such as biophilia, biodiversity promotion, urban microbiome enhancement, air bioremediation in urban settings and the revitalisation of degraded and polluted environments (Beckett, 2021; Cruz & Beckett, 2016; Pollini et al., 2023; Pollini & Rognoli, 2021; Watkins et al., 2020). A notable example of

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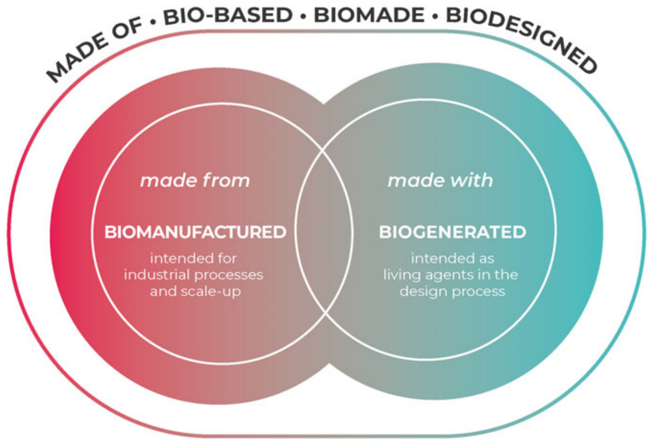

Figure 2. Glossary clarification, as intended in this study.

Bioreceptive Design is the project M.A.R.S., by Alex Goad, which aims to rebuild the coral reef environment by providing a similar infrastructure to support underwater fauna.[3] Bioreceptive materials are predominantly inert (a characteristic observed in most case studies, although the concept of hybrid materials capable of being bioreceptive for one organism while serving as a substrate is also possible[4]). This inertness must not complicate their positioning on the taxonomic scale; if we consider the abiotic and biotic amalgamation resulting from the colonisation of bioreceptive materials, viewing it as a semi-living composite material, it may be aptly situated from the middle to the right side of the taxonomic scale (since bioreceptivity always foresee a living counterpart). Bioreceptive materials inherently anticipate the strong agency of living organisms, which, by colonising the designed material, also influence its future aesthetics through spontaneous expression, co-design and open-ended design.

Clarifying polarities in Biodesign

The extremes of the taxonomic scale represent two different approaches to creating materials and artefacts using living organisms. On the left, there's a focus on industrialisation, scalability and biotechnological implants. On the right, there's an emphasis on experimental and speculative approaches and the intentional use of living organisms in built and non-built environments for their biological enrichment and restoration. Given these findings, and for the purposes of this taxonomic study, it is important to clarify the reference glossary around these two polarities (exemplified in Figure 2).

The terms 'biomanufactured' and 'biogenerated' both refer to materials and products of biological origin but come with significant distinctions in their approach to production processes. With the term 'biomanufactured', we address all the materials and objects obtained from the use of living organisms within industrial processes aimed at scalability.[5] The biomanufacturing industry foresees the use of biological systems (e.g. living microorganisms) for the production of commercially relevant biomolecules, food, energy and materials (Zhang et al., 2016). These materials are produced in a controlled and targeted manner through laboratory or biotechnological processes, often aiming for practical responses to the quest for sustainable material alternatives.

If the term biomanufacturing is well consolidated for industrial scalability, it is not representative of non-industrial processes that leave more expressive space to the organism. For this reason, we address the case studies in the right part of the taxonomy as 'biogenerated',[6] highlighting the degree of co-design with the living organisms and the freedom granted to them. This side of the taxonomic scale concerns the collaborative and uncertain agency of the organism, experienced through a more iterative and DIY design approach.

As reflected by the taxonomy, the substantial distinction between biological industrialised processes and more intimate and experimental ones is mainly based on the scale of operation and on the degree of freedom granted to the organism during the design process. Both conditions can significantly modify the project results, meanings, values and narratives. The next two images aim to visually clarify this concept through case studies.

Figure 3 illustrates this duality in terms of human/non-human interaction. On the left, it depicts how the automation of production processes leads to a functional relationship, often driven by practical considerations of biosecurity and maintenance practicalities. On the right, we see designer Diana Scherer tending to one of her living creations during the New Material Awards exhibition and award ceremony at Milan Design Week in 2016. In this image, the designer is touching the roots of the plants that constitute her Biodesign work, assessing their health and moisture levels. This intimate interaction reflects a profound connection and an understanding of the living material that arises from senses (touch in this case), relational experience and observation. This duality is underpinned by scale (standardised or experimental productions) and the consequent condition for empathy. It parallels human relationships with plants and animals, such as large-scale cultivations and breeding on one side and the care for houseplants and pets on the other.

Figure 4 highlights the aesthetics of the two distinct approaches. On the left, we have scalability: the mycelium packaging maintains an organic texture and is never identical to itself on the microscale, but the general dimensions on the macroscale are respected in their industrial replicability. On the other side, the uncertainty of an experimental and DIY-Bio approach grants the mycelium with the freedom to generate unexpected, always different finishings and shapes of a lampshade. Such vital aesthetics can generate fascination, wonder and surprise (Parisi and Shetty, 2020), clearly showing the concept of *co-design with the living* and the possibility of an open-ended design.

The taxonomic scale can also be a useful tool to evaluate how a category of organisms can be approached differently, giving rise to multiple application possibilities. Figure 5 showcases three projects reliant on algae, displaying them at different positions on the scale.

On the left there's an industrial solution by *Evoware*, an Indonesian company currently producing seaweed bioplastic for packaging.[7] In the middle, the project *Indus* - a bioreactor wall system based on modular tiles for bioremediation, where modules are an example of bioreceptive design, accommodating a seaweed-based hydrogel to clean heavy wastewater materials: here, the algae grow in a given shape and are embedded in the hydrogel. On the right, the project *Biogarmentry* shows the possibility of creating biodegradable living textiles capable of photosynthesis:[9] the designer Roya Aghighi and a group of scientists at the University of British Columbia developed the first proof of concept for the survival of photosynthetic living cells on natural fabrics;ince the life cycle of the living photosynthetic textile is directly dependent on the user's attention, 'the work challenges

Figure 3. Visualising Biodesign polarities part 1: comparing human/non-human interactions. On the left, Mycelium Foundries[26], representative of the industrial processes; on the right, Diana Scherer watering her living artefact during an exhibit, representative of an experimental and relational design approach.[27]

Figure 4. Visualising Biodesign polarities part 2: comparing design approaches and the resulting aesthetics. On the left, Ecovative Packaging,[28] representative of the industrial approach; on the right Myx lamp by Jonas Edvard,[29] representative of an experimental Biodesign approach.

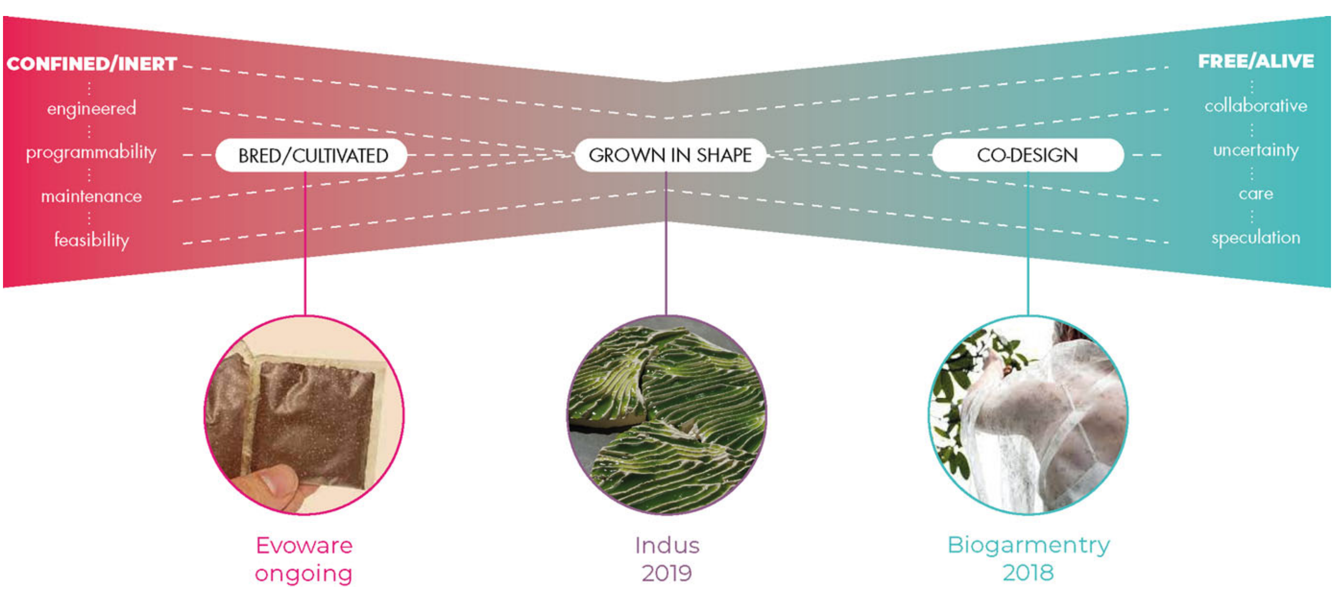

Figure 5. Visualising materials and projects relying on algae, from feasible to speculative solutions.

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users' relationship to clothing while acting as a catalyst for behavioural change'.[10] Biogarments are thus conceived to come with care instructions to help the user keep their Biogarment alive; according to the designer, this might encourage a shift in our current perceptions of fashion, assuming that in a world where garments are dependent living beings, we might build a more intimate relationship with our clothes through caring. This project recalls the importance of care (Puig de la Bellacasa, 2017), focusing on the relationship between users and products and how this might affect users' feelings and worldviews, also resulting in behavioural changes.

As shown, the proposed taxonomy can serve as a framework to examine how Biodesign approaches living organisms, spanning from feasibility to speculation. It can also provide insights into how designers navigate the scale, transitioning from one side to another. In fact, it's not unusual for speculative concepts to evolve into the actual market in just a few years (Rognoli et al., 2021). This highlights how the two ends of the spectrum can influence each other through recurring feedback loops:his dynamic process is indeed driving both desirable visions of the future and market developments.

Inner and outer sustainability: Biodesign's feedback loops among speculation and feasibility

The dichotomy of the taxonomic scale highlights two of Biodesign's key aspects of sustainability that can be further linked to inner and outer sustainability (Ives et al., 2020). Outer (or external) sustainability is a practical form of sustainability, defined by feasible solutions to environmental issues. Outer sustainability stands for those broader socio-economic structures, governance dynamics and technology changes, constituting the external world on which most of the sustainability science has been focusing so far (Ives et al., 2020; Wamsler et al., 2021). In the biotechnology field, feasible material solutions scalable in the short term fall into the left side of the taxonomy, referring to the realm of practical solutions for outer sustainability. The inner dimension of sustainability is described by Horlings as 'an individual process of change from the inside out, based on a person's values, beliefs, and attitudes' needed for the transformation to sustainability (Horlings, 2015). Inner sustainability refers to the inner dimension of the individual, also addressing consciousness, worldviews, spirituality and human–nature connectedness (Woiwode et al., 2021), potentially influencing a change in behaviour. The need for more integrative approaches that link inner and outer dimensions of sustainability to support transformation across individual, collective and system levels has also been recognised at intergovernmental levels (Ives et al., 2023). Moreover, scholars agree that behavioural change would have an undisputed benefit for the success of biomanufacturing sustainability, declaring that without such perspective shift, even the most sustainable production processes will not fit with the limits of the planet (Ginsberg & Chieza, 2018; Hildebrandt et al., 2021).

Biomanufactured materials for conventional sustainability

Biomanufacturing is seen as a key technology that replaces conventional materials with more sustainable, biocompatible, rapidly renewable and biodegradable derivatives from nature (Mironov et al., 2009a, 2009b; Myers, 2012). LCA is a trusted tool for evaluating the environmental impacts of materials and products (Pollini & Rognoli, 2021). The first LCA evaluations of biomanufactured products confirm the hypothesised advantages of adopting biological processes but also reveal some trade-offs related to industrialisation, which are detectable only through in-depth analysis. Although these materials' production processes are biology-driven, achieving the scalability and efficiency required by industrial reproducibility can still have environmental impacts.

For example, the first LCA studies on fermentation-based biomanufacturing (from bioengineered bacteria to bacterial cellulose) outline the importance of organizing the activities around agro-industry waste to limit the impacts otherwise present in such an industrial process; moreover, they highlight that electricity consumption during the manufacturing process is one of the major environmental impacts (Lips, 2021; Narodoslawsky et al., 2015; Bardone et al., 2020), together similar ones related to fresh water and wastewater (Forte et al., 2021; Chen & Liu, 2021). Also regarding mycelium, the energy used for sterilisation, incubation, production and drying phase to obtain mycelium-based materials or products can be significant (Jones et al., 2021; Silverman, 2018; Volk et al., 2024). Comparative LCA studies confirm the overall lower environmental impact of mycelium compared with conventional expanded polystyrene materials in the packaging sector (Enarevba & Haapala, 2023); also in the insulating sector, mycelium shows better environmental features when compared to traditional plastic insulation (Alaux et al., 2024). In a study analysing the sustainability of novel textile materials through a comparative LCA between (I) animal leather, (II) bacterial cellulose leather-like material and (III) a bio-based leather-like material derived from pineapple, feedstock circularity was highlighted as very important in reducing overall production's impacts; moreover, this study was one of the first pointing out that, to reach bovine leather performances and durability, leather substitutes often rely on non-biodegradable finishings (such as PU), with a consequent negative impact on the production phase and the end-of-life of the material (Hildebrandt et al., 2021). The literature identifies the potential of biomanufacturing for the circular economy, where the organisms used can be connectors between one production system and another, thanks to their ability to transform agro-industry waste into valuable materials and products (Devadas et al., 2021; Jang et al., 2017; Meyer et al., 2020; Ubando et al., 2020). Even in this case, however, some aspects must be considered to guarantee the sustainability conditions for biomanufactured materials. For example, to ensure sustainable feedstock sourcing for fermentation and biomanufacturing processes it is important to rely on first-generation biomass grown sustainably and possibly derived from wastes (Lips, 2021; Ubando et al., 2020).

This brief overview shows the potential of LCAs in identifying the advantages and current drawbacks of biomanufacturing processes. It also highlights recursive environmental issues, such as the need for water and electricity containment and the necessity to integrate these processes within circular economy material flows to fully express the sustainable potential of such bio-based productions. Despite the potential for sustainability in the field, there is limited quantitative data available due to the novelty of the biomanufactured materials. Most startups, companies and labs tend to prioritise material development over predictive LCA studies during the research and development phase. This is because the research phase is mostly focused on producing proofs of concept, with the intention of making them more efficient for scalability at a later time (Bak-Andersen, 2021; BIOFABRICATE 2022 Summit Report). However, conducting LCAs of the first biomanufactured products entering the market and partial LCAs of processes still in the research phase is a necessary step to gain a more realistic understanding of the ecological potential of biotechnologies. As noted by Raman, ‘environmental impacts must be predicted and weighted into our collective decision-making on the growth and evolution of this field’ (Raman, 2021). Many authors in the field highlight the importance of predictive LCA to foresee ecological hot spots and improve processes starting from preventive assessments (to name a few: de Araújo e Silva et al., 2020; Lynch & Pierrehumbert, 2019; Mattick et al., 2015; Narodoslawsky et al., 2015; Raman, 2021; Saavedra del Oso et al., 2023).

Overcoming conventional sustainability: connections between Biodesign and Regenerative Design

In contrast to the left side of the taxonomic scale, projects on the right side of the scale aren’t so easy to be assessed through conventional sustainability metrics. Speculative projects often envision an interaction with living organisms, pushing for inner sustainability through critical thinking. Latro Lamp by Mike Thompson[11] is a living lamp based on algae’s bioelectricity, which needs to be fed by the user, asked to provide carbon dioxide by breathing through a hole in the handle; this way, such lighting system is asking for a constant relationship of care. Another lamp, this time powered by bioluminescent bacteria, is Ambio Light by Teresa van Dongen[12]; in this case, the user is asked to swing the object to stimulate the bacteria to emit light. The user engagement leads to a constant observation of the organisms’ reaction, taking care of them and interacting with in order to make the objects work. In both cases, a reconsideration of the relationship with the non-human and a critical reasoning is implied and thus encouraged.

Livingness brings into the design discourse many new features peculiar to the emerging Biodesign materialities, such as self-growing, self-assembly and self-healing abilities. Sensitivity and responsiveness to external stimuli are game-changer features for biodesigned materials and artefacts aiming at embedding living interactions in the design process and fruition (Adamatzky et al., 2021; Adamatzky & Gandia, 2021; Albergati, 2021; Dade-Robertson, 2020; Gilbert et al., 2021). Moreover, many case studies in this category concern bioremediation, bioreceptivity, biophilia and biodiversity enhancement. Some representative case studies can be the living root bridges in the state of Meghalaya, in northeastern India (Shankar, 2015), where *Ficus elastica* trees are used for the construction of bridges; these structures are living architectures that at the same time continue to perform as ecological agents in the forest ecosystem. Many other case studies in this category are related to Bioreceptive Design, as in the case of artecology,[13] a studio focusing on the creation of ‘intentional habitat’ designed specifically for building biodiversity and bio-abundance in different environments and ecosystems. Another example is NOTBAD (Niches for Organic Territories in Bio-Augmented Design),[14] a project by Richard Beckett and Sean Nair that explores the integration of beneficial microbes into building materials through bioreceptive surfaces as a novel approach to prevent the spread of antimicrobial resistance in the built environment (Beckett, 2021).

Unlike the left side of the scale, it is not easy for these case studies to be assessed with conventional sustainability parameters (e.g. LCA). Here, the potential of the living qualities of the organisms involved in the Biodesign process pushes conventional sustainability based on limiting the environmental impacts of production with the ability to interact, restore, remediate and regenerate the environment. These aspects are hardly analysed through conventional sustainability metrics, and there are no clear shared metrics to date to evaluate these projects in terms of their positive impact- if not based on the observation of their effectiveness over time. The impossibility of fitting in conventional sustainability metrics can be discussed in reference to the fundamental theory of Regenerative Design (Reed, 2007), which sees the limits of ‘sustainability’ as currently intended and promotes its overcoming through regenerative, resilient and adaptive cultures. Instead of focusing on less impacting productions, Regenerative Design claims that ‘it is necessary to learn how one can participate with the environment by using the health of ecological systems as a basis for design’, thus moving from a fragmented vision to a system-based approach focused on mutually beneficial relationships (Reed, 2007). If Regenerative Design refers to a system of technologies and strategies aimed at supporting the evolutionary health of social and environmental systems, Regenerative Development is a system of developmental technologies and strategies that works to enhance the ability of living beings to co-exist, supporting biodiversity, complexity and co-evolution among species (Mang and Reed, 2017). Accordingly, Regenerative Sustainability focuses on transforming worldviews and paradigms addressing ‘post-sustainability scenarios’ (Gibbons, 2020) with clear reference to the values of inner sustainability, thus reflecting part of the findings emerged from the taxonomical scale.

Regenerative Design offers a reading lens for those case studies that are not quantifiable from the point of view of sustainability as currently understood but aim to design human systems and built environments capable of co-evolving with natural ones (Mang, 2001; Mang et al., 2016). There are important connections between Regenerative Design and Biodesign, overcoming the more simplistic association based on the biological regenerative process. Three concepts, in particular, resonate among the two disciplines, such as the importance of understanding the place/system and its potential, the idea of humans taking a new co-creative participatory role in the system and their co-evolution with the system itself. These guiding principle at the core of Regenerative Design somehow resonate with the ideas of ‘symbiotic relationships’, ‘more-than-human’, ‘multispecies’ and ‘co-creation’, often addressed in Biodesign to highlight the (re)discovery of human-nature relationship through its practice.

Recently, the academic discourse on Biodesign is starting to consider the fundamental principles of Regenerative Design (Karana et al., 2023; Pollini, 2023; Williams & Collet, 2020). Moreover, some Biodesign case studies started to be associated with Regenerative Design. The living root bridges have been defined as an example of Regenerative Design (Middleton et al., 2020). Mycelium bricks for architecture, described as a soft (non-linear) and regenerative system, have been depicted as ‘an alternate future in which regenerative architectural materials transform over their lifetime, adapting to change and serving needs that are simultaneously structural, aesthetic, and visceral’ (Dahmen, 2017). To deepen this discussion, the next paragraph will analyse Biodesign case studies by crossing the findings of the taxonomic scale and the Regenerative Design framework.

Analysing biodesigned artefacts in the Regenerative Design framework

Regenerative Design is conceived as ‘a system of technologies and strategies, based on the understanding of the inner working of

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ecosystems that generates designs that regenerate socio-ecological wholes (i.e. generate anew their inherent capacity for vitality, viability, and evolution) rather than deplete their underlying life support systems and resources' (Mang and Reed, 2017). Regenerative Design is a systemic approach; therefore, biodesigned living or non-living artefacts might be part of a regenerative system, but they can hardly be addressed as regenerative by themselves. A fruitful interview with Bill Reed (2022) helped the authors clarify this concept,[15] further drawing parallels between the taxonomic scale and the *Ecological Strategies for Regenerative Design* (Regenesis 2000–2024). Figure 6 is the result of a discussion between the first author and Bill Reed on the possibility of positioning biomanufactured, biogenerated and bioreceptive design case studies within the Regenerative Design framework (diagram by Pollini and Reed, 2022, reported in Pollini, 2023).

In the following subsections, several case studies are discussed based on their position on the taxonomy proposed here by the authors in resonance with the Regenerative Design scale (Figure 6), which progresses from anthropocentric to biocentric through different *Levels of Ecological Strategies for Sustainability* (Mang & Reed, 2017).

Stabilised biofabricated materials

Most of the biomanufactured materials match the level of conventional sustainability in the Regenerative Design framework. Here are stabilised materials created by living organisms and later made inert to reach the market as alternative sustainable materials. As shown by the diagram, we find here for example bacteria-based dyeing for fabrics by Chieza (from 2017),[16] and the products of two of the best-known biotech industries: the American Modern Meadow[17] and the European Mogu.[18] This level corresponds to the extreme left polarity on the taxonomical scale, meaning biofabrication processes aimed at control and scalability.

Bioreceptive/living materials or artefacts unable to self-sustain

At a subsequent level are bioreceptive or living materials/artefacts unable to self-sustain; here the organism has a limited lifespan and requires human care/maintenance while alive. Among the case studies cited here are the European project Fungar (EU H2020),[19] a research that hypothesises mycelium in its living state for the creation of living architectures and biosensors, and the hydroponic textiles of J. Olmedo (2016)[20] and Latro Lamp (2017).[21] All these case studies identify systems that are alive in their use phase, requiring constant care for surviving (and functioning) in the given timeframe. This level describes living artefacts embedding biological materials, mimicking nature's way of building things, but not its ability to regenerate life with independent self-propagating processes.

Bioreceptive/living materials or artefacts with restorative abilities but unable to self-sustain

For Regenerative Design, the restorative level describes a more biocentric approach (Mang & Reed, 2017). Here are bioreceptive or living materials/artefacts with restorative abilities but unable to regenerate without further human maintenance. Once the design is installed/planned, it needs continuous adjustments by humans, who act like 'gardeners' (Collet Carol, 2013; Mang & Reed, 2017). The main difference from the previous level is that the livingness of the organisms not only serves a designed function, but it also contribute to restore the environment. For example, the living root bridges (Watson, 2021) serve as bridges; however, as living plants, they also contribute to photosynthesis or sheltering animals in the first place. Their function as bridges can only be perpetuated thanks to continuous human maintenance. Pnat (2019) created an indoor greenhouse capable of purifying the air through phytoremediation[22]; however, it is a closed system that requires maintenance and technology. Biogarmentry (2019) purifies the air while serving as a fashion item; however, its purifying action depends on the user's maintenance actions in keeping the algae alive.

Bioreceptive/living materials or artefacts with restorative abilities, able to regenerate the system

The final level on the scale of Regenerative Design corresponds to bioreceptive and living materials/artefacts with restorative abilities but also able to regenerate their system. This means that once the design is installed, it will be colonised (or replicate itself) to the point that it will evolve in relationship with its own environment in a regenerative way. Only within this last levelwe may find case studies where the organism kept alive is not only able to regenerate independently but can actively regenerate its system, integrating itself and contributing to the well-being of other species as well – for example, by purifying water as in the case of mussels bioremediation (Sicuro et al., 2020). When it comes to bioreceptive materials, we can say that they are regenerative systems whenever they can provide a welcoming space for vital systems to evolve and thrive on their surface with no further human maintenance – for example, by creating green surfaces capable of increasing urban biodiversity as in the case of bioreceptive concrete (Manso, 2014) or offering shelter and foothold for life in coral reefs, as in the case of M.A.R.S.[23]

As shown by Figure 6, not all Biodesign projects are sustainable in a radical and post-anthropocentric way in reference to the Regenerative Design framework; only a part of them manages to cross the threshold of conventional sustainability, tending towards restorative and regenerative processes. This higher level coincides with the artefact's ability to create a system able to regenerate. To evaluate this possibility, we can say that if a system can evolve, self-organise and propagate, it can be addressed as an example of Regenerative Design (Pollini, 2022). No artefacts alone can reach the Regenerative Development level (the last and most virtuous of the Regenerative Design framework), but Regenerative Design solutions can be a significant part of it. This level supports co-development where autonomous regenerative systems co-exist: they can infact be simply experienced, enhance biophilic environments, restore depleted habitats and ultimately co-evolve with human beings. For instance, we can affirm that the ongoing development of a biotic and abiotic system, created through designed bioreceptivity, will occur in co-evolution with humans (Figure 7).

Healing materialities: an overarching conceptual framework defining the inner and outer sustainable nature of Biodesign

In line with the framework of Regenerative Design, some Biodesign case studies seem to have the right features to be framed as restorative and regenerative solutions. In the attempt to frame biodesigned materials and artefacts for conventional and

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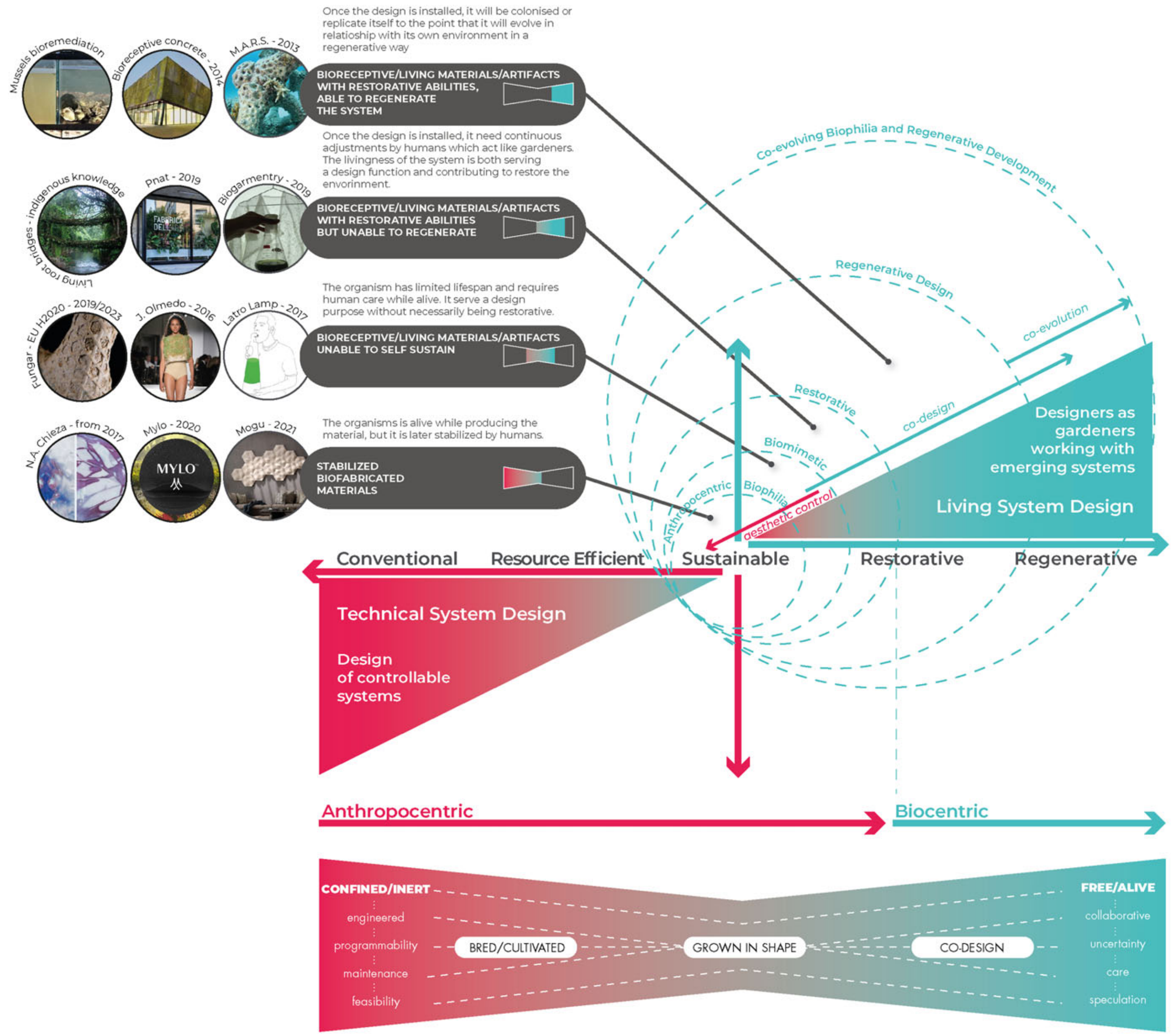

Figure 6. Comparison between the taxonomic scale and the Regenerative Design framework (Regenesis 2000–2024) with case studies positioning.

regenerative sustainability, the concept of Healing Materialities[24] inscribes both practical solutions enabled by biotechnologies, as well as the restorative and regenerative features of more experimental biodesign explorations. The word 'healing' has biological and socio-symbolic meanings; in Biodesign, this concept is strongly emphasised. First, the etymology of the word 'healing' is also related to the concept of wholeness, derived from the ancient English root, hǣlan (restore to sound health), and to the condition or state of being 'whole' – a concept extremely resonating with the 'state of co-evolution' addressed in the Regenerative Development theory (Mang and Reed, 2017). Secondly, the concept of regeneration in biology is related to a healing process through which living beings restore organisms' injured body parts, and its broader interpretation can be applied to the ability of species and biosystems to recover their own. Self-healing and biocompatibility are material features that can become design abilities to fit human existence in ecological systems. Biophilic Design (Söderlund, 2019) has been related to a 'healing' power, referring to the beneficial influence of a biophilic approach in architecture on the human body and mind (Salingaros, 2015). The need for a 'healing culture' is also felt in the design community: the exhibition Broken Nature, curated by Paola Antonelli in 2019, proposes design as a 'repair strategy', advocating for restorative and 'allocentric design', an approach able to act on the multiple bonds that connect human beings to their environments and other species, in every order of magnitude and system[25] (Antonelli & Tannir, 2019).

In this study, the adjective 'healing' assumes both the polarities of the taxonomical scale, suggesting that Biodesign has a dual nature in fostering a more aware and respectful ecological turn, acting both through practical solutions (enhancing current outer sustainability targets) and as a cultural mediator, fostering inner sustainability and more regenerative paths. Healing Materialities is the conceptual framework connected to the Biodesign taxonomic scale and its inner and outer sustainable nature; it arose from the

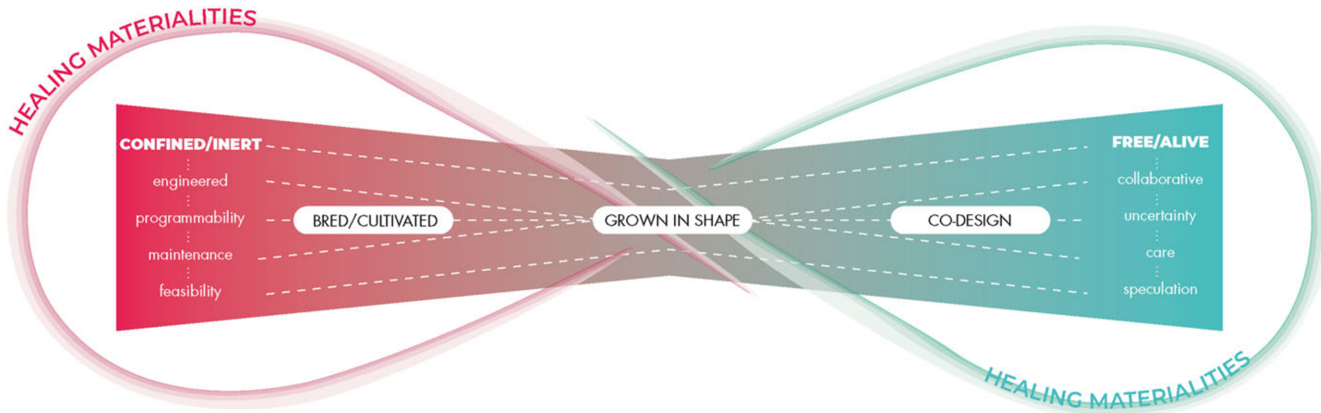

Figure 7. The dual nature of Biodesign through the Healing Materialities conceptual framework highlights the feedback loop between the two polarities.

need to describe the variety of sustainable possibilities offered by Biodesign and to highlight the feedback loop between the two polarities of the scale – among applied research and speculation, material possibilities and visions. These polarities nurture each other. In fact, it is not unusual for speculative projects to become feasible after a few years, starting as a diegetic prototype and ending up in the market.

The concept of Regenerative Design, based on the idea that sustainability should not only avoid harm to the environment but actively participate in its restoration, has significantly influenced this conceptual framework. Healing Materialities also foresees designed human systems that can co-evolve with natural ones through participation and design actions. The comparison made between the taxonomic scale and the Regenerative Design framework further validates the affinities between the two approaches, broadening the possibilities offered by biodesigned materials and artefacts- from sustainability to its overcoming, towards a more regenerative attitude.

To conclude, the adjective 'healing' assumes both a philosophical and concrete meaning, suggesting that Biodesign has a dual nature in fostering a more aware and respectful environmental adaptation: Healing Materials are biodesigned solutions that propose technical and/or philosophical responses to human-nature disconnectedness.

Sustainability remains an elusive and evolving concept, often promoted within the field and sparking the engagement of biodesigners. The Biodesign taxonomic scale and the Healing Materialities framework presented here reflect the Regenerative Design idea of sustainability as evolutionary health, supporting life through a diversity of species and relationships. This contribution aims to clarify Biodesign's role in achieving new sustainable models of production and co-existence.

Conclusion and impact statement

To better frame Biodesign's potential towards sustainability, a taxonomic scale and the derived conceptual framework of Healing Materialities have been proposed to spotlight both technical and conceptual biodesigned solutions in response to human-nature disconnectedness.

The study highlights the double nature of Biodesign: on one side, biomanufactured solutions responds to conventional sustainability, mainly serving substitution strategies to date; on the other hand, some biodesigned projects cannot be fully represented by the current sustainability metrics, due to living organisms' ability to evolve, grow, propagate, sense and react, thus resonating with the concepts of Restorative and Regenerative Design, while fostering radical and post-anthropocentric worldviews.

Biodesign is an emerging but unfolding phenomenon; therefore, the observations discussed in this article on the taxonomic scale (based on the case studies' positioning) may change, confirming it as a tool to gather the field's evolution over time.

Data availability statement. Data availability does not apply to this article.

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Competing interests. The authors have no conflicts of interest to declare for this publication.

Ethics statement. Ethical approval and consent are not relevant to this article type.

Notes

1 Case studies were collected from 2019 to 2023, during the first author's doctoral research. Seventy-eight case studies were selected with a qualitative approach based on technical, scientific and aesthetic innovation. The taxonomy presented here emerged from the peculiarities found in these first case studies, grouped by affinities of features and significance into two main areas describing distinctive approaches in Biodesign (Pollini, 2023).
2 An early version of this taxonomy was developed during the first author's doctoral research (Pollini, 2021). A final and updated version of the taxonomy was first published in the Author's PhD thesis (Pollini, 2023).
3 Retrieved in April 2023 from: https://www.alex-goad.com/mars
4 The possibilities of interaction between organisms is another aspect explored in Biodesign that can lead to living organisms' symbiosis, as in the case of the MYCO-ALGA tiles developed by the design studio bioMATTERS. Retrieved in November 2023 from: www.biomatters.org
5 The term 'biofabrication' is also quoted similarly addressing industrial processes (Groll et al., 2016; Mironov et al., 2009; Lee, 2020; Raman, 2021).

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6 The term is derived from the concept of biogenesis, which is intended as the 'development of life from preexisting life'. In the purpose of this study, the term highlights the generative and active agency of organisms embedded in the design process. Biogenesis meaning was retrieved in April 2023 from: https://www.merriam-webster.com/dictionary/biogenesis https://www.merriam-webster.com/dictionary/biogenesis
7 Retrieved in April 2023 from: http://www.evoware.id/
8 Retrieved in April 2023 from: https://www.ucl.ac.uk/bartlett/architecture/news/2019/apr/innovative-bio-integrated-design-wins-water-futures-design-challenge
9 Retrieved in June 2024 from: https://designawards.core77.com/personal-accessory/83837/Biogarmentry-Living-and-Photosynthetic-Textile
10 From the designer's website. Retrieved in April 2023 (no longer existing in June 2024) from: www.royaaghighi.com/biogarmentry.html
11 Retrieved in December 2023 from: nextnature.net/story/2012/latro-algae-lamp
12 Retrieved in December 2023 from: www.teresavandongen.com/Ambio
13 Retrieved in December 2023 from: www.artecology.space
14 Retrieved in December 2023 from: www.ucl.ac.uk/bartlett/architecture/research/building-wellbeing/niches-organic-territories-bio-augmented-design
15 Pollini, B. (2022). Healing Materialities in conversation with Bill Reed. Retrieved on June 2024, from: https://healing-materialities.design/home/#bill_reed
16 Retrieved in April 2023 from: https://www.natsaiaudrey.co.uk/
17 Retrieved in April 2023 from: https://www.modernmeadow.com/modern-meadow-materials
18 Retrieved in April 2023 from: https://mogu.bio/
19 Retrieved in June 2024 from: https://cordis.europa.eu/project/id/858132
20 Retrieved in April 2023 from: https://www.jacobolmedo.com/
21 Retrieved in June 2024 from: https://nextnature.net/story/2012/latro-algae-lamp
22 Retrieved in April 2023 from: https://www.pnat.net/it/fabbrica-dellaria/
23 Retrieved in December 2023 from: https://www.alex-goad.com/mars
24 This definition is derived from a lecture the first author held at the conference Caring Matters, organised within the project TAKING CARE by the Research Center for Material Culture, presenting the early PhD research findings in a workshop session named Healing Materialities, where she shared her early findings on the potentialities of Biodesign emerged under this perspective (Accessible from: www.materialculture.nl/en/caring-matters-museums-and-objects).
25 Retrieved in December 2023 from: www.brokennature.org/reparations-by-design
26 Retrieved in December 2023 from: www.ecovative.com/pages/mycelium-foundry
27 Photo credits: Barbara Pollini, Milan Design Week, 2016
28 Retrieved in June 2024 from: https://mushroompackaging.com/products/hudson-hemp-tincture-packaging; Image source retrieved in December 2023 from: https://www.vogue.com/article/mycelium-packaging-could-help-solve-beauty-industry-waste-problem
29 Retrieved in June 2024 from: https://www.jonasedvard.com/myx

Connections references

Dade-Robertson, M (2023) New seeds? *Research Directions: Biotechnology Design*. 1, E15. https://doi.org/10.1017/btd.2023.9.

References

Adamatzky A and Gandia A (2021) Living mycelium composites discern weights via patterns of electrical activity. *Journal of Bioresources and Bioproducts* 7, 26–32. https://doi.org/10.1016/j.jobab.2021.09.003

Adamatzky A, Nikolaidou A, Gandia A and Chiolerio A (2021) Living wearables from slime mould and fungi. *Revue LINKs series Special Issue* **1**, 93–98.

Alaux N, Vašatko H, Maierhofer D, Saade MRM, Stavric M and Passer A (2024) Environmental potential of fungal insulation: A prospective life cycle assessment of mycelium-based composites. *The International Journal of Life Cycle Assessment* **29**, 255–272. https://doi.org/10.1007/s11367-023-02243-0

Albergati E (2021) *Living Interaction. From User-centered Design to Bio-user System*. Politecnico di Milano. https://www.politesi.polimi.it/handle/10589/175661.

Almpani-Lekka D, Pfeiffer S, Schmidts C and Seo S (2021) A review on architecture with fungal biomaterials: The desired and the feasible. *Fungal Biology and Biotechnology*, **8**, 17. https://doi.org/10.1186/s40694-021-00124-5.

Amobonye A, Lalung J, Awasthi MK and Pillai S (2023) Fungal mycelium as leather alternative: A sustainable biogenic material for the fashion industry. *Sustainable Materials and Technologies*, **38**, e00724. https://doi.org/10.1016/j.susmat.2023.e00724.

Antonelli P and Tannir A (2019) *Broken Nature. 22ª Triennale di Milano*. Electa.

Bak-Andersen M (2021) *Reintroducing Materials for Sustainable Design: Design Process and Educational Practice*. Routledge. https://doi.org/10.4324/9781003109525

Bardone E, Marzocchella A, Bravi M, Aragão J, Costa A, Gilson L, Silva G, Silva S, Macêdo J, Galdino C, Milanez F and Sarubbo L (2020) Analysis of the environmental life cycle of bacterial cellulose production. *Chemical Engineering Transactions* **79**, 2020. https://doi.org/10.3303/CET2079075

Beckett R (2021) Probiotic design. *The Journal of Architecture* **26**, 6–31. https://doi.org/10.1080/13602365.2021.1880822

BIOFABRICATE (2022) Summit Report. Available at: https://www.biofabricate.co/resources.

Camere S and Karana E (2017) Growing materials for product design. *EKSIG2017 - International Conference on Experiential Knowledge and Emerging Materials, Delft, The Netherlands*.

Camere S and Karana E (2018) Fabricating materials from living organisms: An emerging design practice. *Journal of Cleaner Production* **186**, 570–584. https://doi.org/10.1016/j.jclepro.2018.03.081

Camocini B and Vergani F (2021) From human-centered to more-than-human-design. exploring the transition. In *FrancoAngeli Series – Open Access. FrancoAngeli Series – Open Access*. https://series.francoangeli.it/index.php/oa/catalog/book/749.

Carol C (2013) *Alive, New Design Frontiers*. Central Saint Martins. https://www.arts.ac.uk/colleges/central-saint-martins/research-at-csm/alive-new-design-frontiers.

Chen G-Q and Liu X (2021) On the future fermentation. *Microbial Biotechnology* **14**, 18–21. https://doi.org/10.1111/1751-7915.13674

Cruz M and Beckett R (2016) Bioreceptive design: A novel approach to biodigital materiality. *Architectural Research Quarterly* **20**, 51–64. https://doi.org/10.1017/S1359135516000130

Dade-Robertson M (2020) *Living Construction*. Taylor & Francis Group.

Dahmen J (2017) Soft futures: Mushrooms and regenerative design. *Journal of Architectural Education* **71**, 57–64. https://doi.org/10.1080/10464883.2017.1260927

de Araújo e Silva R, Santa Brígida AI, de Freitas Rosa M, da Silva Neto RM, Spinosa WA, Benício de Sá Filho E and Brito de Figueirêdo MC (2020) An approach for implementing ecodesign at early research stage: A case study of bacterial cellulose production. *Journal of Cleaner Production* **269**, 122245. https://doi.org/10.1016/j.jclepro.2020.122245

Devadas VV, Khoo KS, Chia WY, Chew KW, Munawaroh HSH, Lam M-K, Lim J-W, Ho Y-C, Lee KT and Show PL (2021) Algae biopolymer towards sustainable circular economy. *Bioresource Technology* **325**, 124702. https://doi.org/10.1016/j.biortech.2021.124702

Elsacker E, Zhang M and Dade-Robertson M (2023) Fungal engineered living materials: The viability of pure mycelium materials with self-healing functionalities. *Advanced Functional Materials, 33*. https://doi.org/10.1002/adfm.202301875.

Enarevba DR and Haapala KR (2023) A comparative life cycle assessment of expanded polystyrene and mycelium packaging box inserts. *Procedia CIRP* **116**, 654–659. https://doi.org/10.1016/j.procir.2023.02.110

Esat R and Ahmed-Kristensen S (2018) Classification of bio-design applications: towards a design methodology. In *Conference: 15th International Design Conference*, pp. 1031–1042. https://doi.org/10.21278/idc.2018.0531

Forte A, Dourado F, Mota A, Neto B, Gama M and Ferreira EC (2021) Life cycle assessment of bacterial cellulose production. *The International Journal of Life Cycle Assessment* **26**, 864–878. https://doi.org/10.1007/s11367-021-01904-2

Gatto, G., & McCardle, J. (2019) Multispecies design and ethnographic practice: following other-than-humans as a mode of exploring environmental issues. *Sustainability* **2019**, 5032. https://doi.org/10.3390/su11185032

Gibbons LV (2020) Regenerative—The new sustainable? *Sustainability* **12**, Article 13. https://doi.org/10.3390/su12135483

Gilbert C, Tang T-C, Ott W, Dorr BA, Shaw WM, Sun GL, Lu TK and Ellis T (2021) Living materials with programmable functionalities grown from engineered microbial co-cultures. *Nature Materials* **20**, 691–700. https://doi.org/10.1038/s41563-020-00857-5

Ginsberg AD, Calvert J, Schyfter P, Elfick A and Endy D (2017) *Synthetic Aesthetics: Investigating Synthetic Biology's Designs on Nature*. MIT Press.

Ginsberg AD and Chieza N (2018) Editorial: Other biological futures. *Journal of Design and Science*. https://doi.org/10.21428/566868b5

Groll J, Boland T, Blunk T, Burdick JA, Cho D-W, Dalton PD, Derby B, Forgacs G, Li Q, Mironov VA, Moroni L, Nakamura M, Shu W, Takeuchi S, Vozzi G, Woodfield TBF, Xu T, Yoo JJ and Malda J (2016) Biofabrication: Reappraising the definition of an evolving field. *Biofabrication* **8**, 013001. https://doi.org/10.1088/1758-5090/8/1/013001

Guillitte O (1995) Bioreceptivity: A new concept for building ecology studies. *Science of the Total Environment* **167**, 215–220. https://doi.org/10.1016/0048-9697(95)04582-L

Hildebrandt J, Thrän D and Bezama A (2021) The circularity of potential bio-textile production routes: Comparing life cycle impacts of bio-based materials used within the manufacturing of selected leather substitutes. *Journal of Cleaner Production* **287**, 125470. https://doi.org/10.1016/j.jclepro.2020.125470

Hirscher M and Posch I (2023) Human-material interactions as practice for care. DRS 2024, Boston. Available at https://dl.designresearchsociety.org/drs-conference-papers/drs2024/researchpapers/280/.

Horlings L (2015) The inner dimension of sustainability: Personal and cultural values. *Current Opinion in Environmental Sustainability*, **14**, 163–169. https://doi.org/10.1016/j.cosust.2015.06.006.

Hosey G and Melfi V (2014) Human-animal interactions, relationships and bonds: A review and analysis of the literature. *International Journal of Comparative Psychology* **27**. https://doi.org/10.46867/ijcp.2014.27.01.01

Ives CD, Freeth R and Fischer J (2020) Inside-out sustainability: The neglect of inner worlds. *Ambio* **49**, 208–217. https://doi.org/10.1007/s13280-019-01187-w

Ives CD, Schäpke N, Woiwode C and Wamsler C (2023) IMAGINE sustainability: Integrated inner-outer transformation in research, education and practice. *Sustainability Science* **18**, 2777–2786. https://doi.org/10.1007/s11625-023-01368-3

Jang WD, Hwang JH, Kim HU, Ryu JY and Lee SY (2017) Bacterial cellulose as an example product for sustainable production and consumption. *Microbial Biotechnology* **10**, 1181–1185. https://doi.org/10.1111/1751-7915.12744

Jones M, Gandia A, John S and Bismarck A (2021) Leather-like material biofabrication using fungi. *Nature Sustainability* **4**, Article 1. https://doi.org/10.1038/s41893-020-00606-1

Jones O (2009) Nature-culture. In Kitchen R and Thrift N (eds.), *International Encyclopedia of Human Geography*. Elsevier, pp. 309–323.

Karana E, Barati B and Giaccardi E (2020) Living artefacts: conceptualizing livingness as a material quality in everyday artefacts. *International Journal of Design* **14**. http://www.ijdesign.org/index.php/IJDesign/article/view/3957/923.

Karana, E., McQuillan, H., Rognoli, V., & Giaccardi, E. (2023) Living artefacts for regenerative ecologies. *Research Directions: Biotechnology Design* **1**, e16. https://doi.org/10.1017/btd.2023.10

Karana E, Pedgley O and Rognoli V (2013) *Materials Experience: Fundamentals of materials and design (1° edizione)*. Butterworth-Heinemann.

Keune S (2021) Designing and living with organisms weaving entangled worlds as doing multispecies philosophy. *Journal of Textile Design Research and Practice* **9**, 9–30. https://doi.org/10.1080/20511787.2021.1912897

Kim R, Zhou J, Groutars E and Karana E (2022) Designing living artefacts: Opportunities and challenges for biodesign. *Proceedings DRS 2022*. p. 10. https://doi.org/10.21606/drs.2022.942

Lantada AD, Korvink JG and Islam M (2021) Taxonomy for engineered living materials. arXiv:2110.08917 [Cond-Mat, Physics:Physics]. http://arxiv.org/abs/2110.08917.

Lee S, Congdon A, Parker G and Borst C (2020) *Understanding 'Bio' Material Innovations: A Primer for the Fashion Industry*. ©Biofabricate and Fashion for Good 2021. https://it1lib.org/book/11722399/3da5ef?id=11722399&secret=3da5ef.

Lips D (2021) Practical considerations for delivering on the sustainability promise of fermentation-based biomanufacturing. *Emerging Topics in Life Sciences* **5**, 711–715. https://doi.org/10.1042/ETLS20210129

Lynch J and Pierrehumbert R (2019) Climate impacts of cultured meat and beef cattle. *Front Sustain Food System* **3**, 5. doi: 10.3389/fsufs.2019.00005.

Mang P (2001) Regenerative design and the evolution of the sustainable design field. *Design Intelligence* **7**. https://doi.org/10.13140/RG.2.1.2166.3766

Mang P, Haggard B and Regenesis (2016) *Regenerative Development and Design: A Framework for Evolving Sustainability*. John Wiley & Sons Inc.

Mang P and Reed B (2017) *Regenerative Development and Design. Chapter 303*. Encyclopedia Sustainability Science & Technology.

Manicka S, Johnson K, Levin M and Murrugarra D (2022) The nonlinearity of regulation in biological networks. *bioRxiv*. 2021.12.22.473903. https://doi.org/10.1101/2021.12.22.473903

Manso S (2014) *Bioreceptivity optimisation of concrete substratum to stimulate biological colonisation*. [Doctoral thesis, Ghent University].

Maréchal L and Zee E (2024) An introduction to human–animal interaction, book content and considerations. In *Introduction to Human-Animal Interaction*. Routledge.

Mattick CS, Landis AE, Allenby BR and Genovese NJ (2015) Anticipatory life cycle analysis of in vitro biomass cultivation for cultured meat production in the United States. *Environmental Science & Technology* **49**, 11941–11949. https://doi.org/10.1021/acs.est.5b01614

Meyer V, Basenko EY, Benz JP, Braus GH, Caddick MX, Csukai M, de Vries RP, Endy D, Frisvad JC, Gunde-Cimerman N, Haarmann T, Hadar Y, Hansen K, Johnson RI, Keller NP, Kraševec N, Mortensen UH, Perez R, Ram AFJ, . . . Wösten HAB (2020) Growing a circular economy with fungal biotechnology: A white paper. *Fungal Biology and Biotechnology* **7**, 5. https://doi.org/10.1186/s40694-020-00095-z

Middleton W, Habibi A, Shankar S and Ludwig F (2020) Characterizing regenerative aspects of living root bridges. *Sustainability* **12**, Article 8. https://doi.org/10.3390/su12083267

Mironov V, Trusk T, Kasyanov V, Little S, Swaja R and Markwald R (2009a) Biofabrication: A 21st century manufacturing paradigm. *Biofabrication*, **1**, 022001. https://doi.org/10.1088/1758-5082/1/2/022001

Mironov V, Trusk T, Kasyanov V, Little S, Swaja R and Markwald R (2009b) Biofabrication: A 21st century manufacturing paradigm. *Biofabrication* **1**, 022001. https://doi.org/10.1088/1758-5082/1/2/022001

Myers W (2012) *Bio Design: Nature, Science, Creativity*. MoMA and Thames & Hudson.

Narodoslawsky M, Shazad K, Kollmann R and Schnitzer H (2015) LCA of PHA production – identifying the ecological potential of bio-plastic. *Chemical and Biochemical Engineering Quarterly* **29**, 299–305. https://doi.org/10.15255/CABEQ.2014.2262

Ostuzzi F (2017) *Open-ended design: Explorative studies on how to intentionally support change by designing with imperfection* [Dissertation, Ghent University]. http://hdl.handle.net/1854/LU-8539015.

Parisi S and Shetty S (2020) Alive, provocative, surprising: Emotional dimensions of bio-synergistic materials for socially meaningful design. Diseña, 17, Article 17. https://doi.org/10.7764/disena.17.128-159.

Pedgley O, Rognoli V and Karana E (2021) *Materials Experience 2: Expanding Territories of Materials and Design*. Butterworth-Heinemann.

Pollini B (2021) Project 13—Healing materialities from a biodesign perspective. In Pedgley O, Rognoli V and Karana E (eds.), *Materials Experience 2*. Butterworth-Heinemann, pp. 167–170. https://doi.org/10.1016/B978-0-12-819244-3.00008-9

Pollini B (2022) Healing Materialities in conversation with Bill Reed. Available at https://healing-materialities.design/home/#bill_reed.

Pollini B (2023) *Healing Materialities from a Biodesign perspective. Framing biodesigned materials and artefacts for the sustainability transition*. [Doctoral thesis, Politecnico di Milano].

Pollini B and Angelini A (2021) Signs of livingness in design material[itie]s. In *Abstract Book, 21st Annual International Gatherings in Biosemiotics*, Stockholm, Sweden, p. 36.

Pollini B, Contardo T, Paciotti D, Rognoli V (2023) *Bioreceptive Interfaces for Biophilic Urban Resilience*. Nature positive/Design for transformation, Cumulus Antwerp.

Pollini B and Rognoli V (2021) Early-stage material selection based on life cycle approach: Tools, obstacles and opportunities for design. *Sustainable Production and Consumption* **28**, 1130–1139. https://doi.org/10.1016/j.spc.2021.07.014

Pollini B and Rognoli V (2021) Enhancing living/non-living relationships through designed materials. In *CEES 2021, International Conference Construction, Energy, Environment & Sustainability - Responsible Biotechnologies and Biodesign for the Built Environment*, Coimbra, Portugal.

Puig de la Bellacasa M (2017) *Matters of Care: Speculative Ethics in More Than Human Worlds*. University of Minnesota Press.

Raman R (2021) *Biofabrication*. MIT Press.

Reed B (2007) Shifting from 'sustainability' to regeneration. *Building Research & Information* **35**, 674–680. https://doi.org/10.1080/09613210701475753

Rigobello A and Ayres P (2023) Design strategies for mycelium-based composites. In Satyanarayana T and Deshmukh SK (eds.), *Fungi and Fungal Products in Human Welfare and Biotechnology*. Springer Nature, pp. 605–635. https://doi.org/10.1007/978-981-19-8853-0_20

Rognoli V, Petreca B, Pollini B and Saito C (2022) Materials biography as a tool for designers' exploration of bio-based and bio-fabricated materials for the sustainable fashion industry. *Sustainability: Science, Practice and Policy* **18**, 749–772. https://doi.org/10.1080/15487733.2022.2124740

Rognoli V, Pollini B and Alessandrini L (2021) Design materials for the transition towards post-Anthropocene. In Camocini B and Vergani F (eds.), *From Human-Centered To More-Than-Human Design, Exploring the Transition*. Franco Angeli, pp. 101–130.

Saavedra del Oso M, Mauricio-Iglesias M, Hospido A and Steubing B (2023) Prospective LCA to provide environmental guidance for developing waste-to-PHA biorefineries. *Journal of Cleaner Production* **383**, 135331. https://doi.org/10.1016/j.jclepro.2022.135331

Salingaros NA (2015) *Biophilia and Healing Environments: Healthy Principles For Designing the Built World*. New York: Terrapin Bright Green, LLC.

Seddon N, Chausson A, Berry P, Girardin C, Smith A and Turner B (2020) Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375**, 20190120. https://doi.org/10.1098/rstb.2019.0120

Shankar S (2015) Living Root Bridges: State of knowledge, fundamental research and future application. In *IABSE Conference: Structural Engineering: Providing Solutions to Global Challenges, Geneva, Switzerland, September 2015, IABSE Conference Geneva 2015*, pp. 1974–1981. https://doi.org/10.2749/222137815818359474

Sicuro B, Castelar B, Mugetti D, Pastorino P, Chiarandon A, Menconi V, Galloni M and Prearo M (2020) Bioremediation with freshwater bivalves: A sustainable approach to reducing the environmental impact of inland trout farms. *Journal of Environmental Management* **276**, 111327. https://doi.org/10.1016/j.jenvman.2020.111327

Silverman J (2018) *Development and testing of mycelium-based composite materials for shoe sole applications* [Master's Theses, University of Delaware]. http://udspace.udel.edu/handle/19716/23768.

Söderlund J (2019) *The Emergence of Biophilic Design*. Springer International Publishing. https://doi.org/10.1007/978-3-030-29813-5

Tsing A (2013) *More-than-Human Sociality: A Call for Critical Description. In Anthropology and Nature*. Routledge.

Ubando AT, Felix CB and Chen W-H (2020) Biorefineries in circular bioeconomy: A comprehensive review. *Bioresource Technology* **299**, 122585. https://doi.org/10.1016/j.biortech.2019.122585

Veselova E and Gaziulusoy I (2021) When a tree is also a multispecies collective, a photosynthesis process and a carbon cycle: A systemic typology of natural nonhuman stakeholders when designing for sustainability. In Diehl JC, Tromp N and van der Bijl-Brouwer M (eds.), *Proceedings of Relating Systems Thinking and Design (RSD10) 2021 Symposium*. https://aaltodoc.aalto.fi/handle/123456789/110897.

Volk R, Schröter M, Saeidi N, Steffl S, Javadian A, Hebel DE and Schultmann F (2024) Life cycle assessment of mycelium-based composite materials. *Resources, Conservation and Recycling*, **205**, 107579. https://doi.org/10.1016/j.resconrec.2024.107579.

Vuylsteke B, Ostuzzi F, Saldien J and Detand J (2022) *Pathway for Designing with New DIY, Circular and Biobased Materials: Insights from Three Case Studies*. Department of Industrial Systems Engineering and Product Design, Imec, pp. 45–54. https://doi.org/10.1007/978-981-16-6128-0_5

Wakkary R (2021) *Things We Could Design: For More Than Human-Centered Worlds*. The MIT Press. . https://mitpress.mit.edu/9780262542999/things-we-could-design/.

Wamsler C, Osberg G, Osika W, Herndersson H and Mundaca L (2021) Linking internal and external transformation for sustainability and climate action: Towards a new research and policy agenda. *Global Environmental Change*, **71**, 102373. https://doi.org/10.1016/j.gloenvcha.2021.102373.

Wang S, Lim S, Tasmim S, Kalairaj MS, Rivera-Tarazona LK, Abdelrahman MK, Javed M, George SM, Lee YJ, Jawed MK and Ware TH (2024) Reconfigurable growth of engineered living materials. *Advanced Materials* **n/a**, 2309818. https://doi.org/10.1002/adma.202309818

Watkins H, Robinson JM, Breed MF, Parker B and Weinstein P (2020) Microbiome-inspired green infrastructure: a toolkit for multidisciplinary landscape design. *Trends in Biotechnology* **38**, 1305–1308. https://doi.org/10.1016/j.tibtech.2020.04.009

Watson J (2021) Lo-TEK. Design by Radical Indigenism. Taschen.

Williams N and Collet C (2020) Biodesign and the allure of "grow-made" textiles: an interview with carole collet. *GeoHumanities* **0**, 1–13. https://doi.org/10.1080/2373566X.2020.1816141

Woiwode C, Schäpke N, Bina O, Veciana S, Kunze I, Parodi O, Schweizer-Ries P and Wamsler C (2021) Inner transformation to sustainability as a deep leverage point: Fostering new avenues for change through dialogue and reflection. *Sustainability Science, 16*. https://doi.org/10.1007/s11625-020-00882-y.

Zhang Y-HP, Sun J and Ma Y (2016) Biomanufacturing: History and perspective. *Journal of Industrial Microbiology & Biotechnology* **44**. https://doi.org/10.1007/s10295-016-1863-2

Zhou J, Barati B, Wu J, Scherer D and Karana E (2021) Digital biofabrication to realize the potentials of plant roots for product design. *Bio-Design and Manufacturing* **4**, 111–122. https://doi.org/10.1007/s42242-020-00088-2