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Microbial Biomineralisation in Living Artefacts for Regenerative Ecologies: An Overview and Design Pathways

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Abstract. This paper explores the potential of microbial biomineralisation—a biological phenomenon where microorganisms drive mineral formation, generating structures with exceptional mechanical properties—for sustainable design futures. In particular, we discuss how leveraging microbial biomineralisation in designing living artefacts can support regenerative ecologies. Although a few pioneering biodesigners have begun to explore the potentials of microbial biomineralisation for design, a vast design space remains under-explored in the realm of living artefacts. In response, we first characterise a design space by analysing 22 microbial biomineralisation cases from art, design, architecture, materials science, and engineering. We examine the specifics of the organisms and substrates used, the fabrication or growing techniques developed, and the unique design outcomes. Following this, we further analyse these cases through a five-pillar framework of living artefacts for regenerative ecologies, speculating on potential pathways where these cases can be further developed as living artefacts to achieve the specific goals related to these pillars. Our results signal a promising era for designing living artefacts that promote cleaner production practices, foster biodiversity, and cultivate care and sensibilities towards other-than-human entities in our daily lives, by integrating the unique properties of microbial biomineralisation into everyday interactions with living artefacts.

Keywords: MICROBIAL BIOMINERALISATION · LIVING ARTEFACTS ·
REGENERATIVE ECOLOGIES · BIODESIGN · LIVING MATERIALS

1 Introduction

Microbial biomineralisation, the process through which microorganisms influence mineral formation, is a remarkable phenomenon where microorganisms, under specific conditions, generate structures presenting exceptional mechanical properties, such as heightened strength (Ehrlich, 1999; Heim, 2011). This capability has drawn the attention of researchers across diverse scientific fields, for example, biomineralisation processes have been used in soil stabilisation in construction research (Kalkan, 2020; Mujah et al.,

2017; van Paassen, 2011) and the fabrication of durable building bricks in the build environment context (Beatty et al., 2022). In these works, microbial biomineralisation emerges as a responsible, low-impact approach poised to mitigate CO² emissions and promote sustainability within the construction sector. Within this context, the emphasis on keeping organisms alive within biomineralised materials, allowing for the revival of the biomineralisation process during use, has been highlighted as a key strategy for radically sustainable approaches (Achal et al., 2015; Beatty et al., 2022). For instance, in *Self Healing Concrete* by Jonkers (2007), microorganisms remedy cracks and prevent their propagation through biomineralisation, extending the service life of concrete structures.

1.1 Living Artefacts for Regenerative Ecologies

In the flourishing field of biodesign (Myers, 2018)—which entails the integration of living organisms into design processes—ongoing research explores maintaining the vitality of organisms within everyday artefacts, i.e., *Living Artefacts* (Karana et al., 2020), to achieve novel functionalities, behaviours, and expressions. Leveraging the metabolic processes of living organisms, these artefacts are envisaged to foster a symbiotic relationship between humans and microbes, where care for the organisms involved heightens engagement, appreciation, and connection with a broader ecosystem (Risseuw et al., 2024; Zhou et al., 2024). In this context, living artefacts present unprecedented avenues for designers to contribute to regenerative ecologies. *Regenerative ecologies* are dynamic systems where humans and nature coexist and evolve together, fostering mutual support, biodiversity, and ecological resilience (Karana et al., 2023). These systems emphasise the interconnectedness of all life forms, promoting ecological health and sustainability. The authors call for human systems that evolve with natural systems, enhancing their ability to thrive and regenerate while preserving essential life support systems and resources (ibid.).

Karana et al. (2023) introduced a framework aimed at guiding designers in discerning, articulating, and critically evaluating the potential of living artefacts for contributing to regenerative ecologies. This framework identifies five key pillars that living artefacts can support when designed with regenerative thinking. The first pillar, *living artefacts for cyclical material and energy systems*, emphasises extending the regenerative capacities of living organisms across various temporal and ecological scales. Designers are encouraged to align the life cycles of artefacts with the natural cycles of the living organisms involved. The second pillar, *living artefacts for biodiversity*, focuses on designing living artefacts that foster multi-species ecosystems promoting collaborative and creative dynamics, enhancing ecosystem resilience, and supporting nutrient cycles and soil remediation. The third pillar, *living artefacts for more-than-human sensibilities*, involves creating mutually beneficial relationships between humans and other-than-human species, promoting understanding and appreciation of diverse needs, scales, agencies, and temporalities. The fourth pillar, *living artefacts for ecological literacy*, highlights the potential of living artefacts to cultivate awareness and knowledge about ecological principles and phenomena, such as nutrient cycles and metabolic processes of various species. Lastly, the fifth pillar, *living artefacts for culture change and holistic worldviews*, addresses integrating living artefacts into everyday practices to mend the cognitive separation between humans and nature, fostering a deeper connection and appreciation of nature. The authors

stress that to design living artefacts that support regenerative ecologies through these pillars, designers should develop an adequate understanding of living organisms, including both humans and other living entities, and their entangled relationships within the ecosystems (ibid.).

1.2 Research Goal and Contributions

Biodesigners have demonstrated diverse potentials of biomineralisation over the past decade. However, there is a gap in investigating the potentials of the biomineralisation process for regenerative ecologies. To address this gap, we conducted an extensive analysis of 22 microbial biomineralisation cases across art, design, science, and engineering. Based on this analysis, our paper makes two main contributions to the biodesign field. Firstly, it unpacks the notion of microbial biomineralisation for design by providing a comprehensive vocabulary and design space. Secondly, it presents design pathways to leverage microbial biomineralisation in living artefacts for regenerative ecologies.

2 Microbial Biomineralisation in Science and Engineering

Microbial biomineralisation is a process where microorganisms facilitate mineral formation, precipitating minerals from the environment (Heim, 2011). The study of microbial biomineralisation began in the late 20th century, marked by significant breakthroughs in understanding how microorganisms influence mineral formation (Ehrlich, 1999; Lowenstam, 1981; Lowenstam & Weiner, 1989). Early discoveries, such as identifying bacteria involved in mineral precipitation, laid the foundation for exploring biomineralisation in sustainable material development across various engineering fields (Achal et al., 2015; Akyel et al., 2022; Beatty et al., 2022; Phillips et al., 2013). For example, the biomineralising bacterium *Sporosarcina pasteurii* (*S. pasteurii*, formerly *Bacillus pasteurii*), combined with the polyglutamate-producing *Bacillus paralicheniformis*, has led to the development of nacre-inspired composites (Spiesz et al., 2019). These materials demonstrate remarkable mechanical properties, such as high toughness, extensibility, and stiffness, surpassing those of natural nacre. Combining these bacteria with *Gluconacetobacter hansenii*, known for its cellulose production, has resulted in fully biodegradable composites with high toughness and impact resistance (Yu et al., 2021).

Building on the findings, researchers explored a diverse range of microorganisms, including bacteria (Schüler & Frankel, 1999; Wei et al., 2015), fungi (Bindschedler, 2016; Gadd, 2021), and algae (De Vrind-De Jong & De Vrind 1997; Demes et al., 2009), in microbial biomineralisation. Among those, *S. pasteurii* has been one of the most widely used organisms due to its high urease activity, which efficiently catalyses the hydrolysis of urea into ammonia and carbon dioxide, thereby promoting calcium carbonate (CaCO_3) precipitation (see, e.g., Achal et al., 2009; Whiffin et al., 2007). The high negative surface charge, robust cell structure, and optimal growth correlation with urease production of *S. pasteurii* further enhance its efficacy in biomineralisation (Spiesz et al., 2019; Yu et al., 2021). This particular process, where *S. pasteurii*, among others, induce mineral precipitation, in this case calcium carbonate, through enzymatic reactions

that modify the local environment to facilitate crystal growth, is called Microbial Induced Calcite Precipitation (MICP) (Mortensen et al., 2011).

The potential of MICP, which is a form of biocementation (Cheng & Shahin, 2019), has been explored for soil stabilisation (see, for example, Kalkan, 2020; Mujah et al., 2017; van Paassen, 2011) and durable construction materials (e.g., Biomason, 2012; Heveran et al., 2020). MICP has been further investigated by incorporating spore-forming bacteria from the genus *Bacillus* into concrete, enhancing its durability and lifespan (Jonkers, 2007). This material utilises the natural process of biomineralisation to repair cracks that occur in concrete structures over time, thereby reducing their maintenance costs and extending the service life (Jonkers & Schlangen, 2008). Advancements in microbial biomineralisation suggest new directions for the development of Engineered Living Materials (ELMs) (Nguyen et al., 2018; Gilbert & Ellis, 2019), as exemplified by self-healing concrete (Jonkers, 2007). In this space, one particular exciting avenue is the utilisation of the CO₂ capture potential of photosynthetic cyanobacteria during biomineralisation processes (Heveran et al., 2020; Reinhardt et al., 2023).

Successful biomineralisation depends on environmental conditions such as pH, temperature, and availability of mineral precursors (Joshi & Baskar, 2022). Additionally, the presence of organic matrices, like extracellular polymeric substances produced by microorganisms, also plays a crucial role. Optimising these conditions in laboratory settings allows for the customisation of biomineralised materials to specific design needs. Yet, despite its potential, microbial biomineralisation faces challenges such as scalability, control over mineral properties, and long-term stability (Achal et al., 2015; Wu et al. 2021). Future research is expected to explore interdisciplinary approaches in the development of materials with microbial biomineralisation, with refined control over the processes and microbial strains (Joshi & Baskar, 2022; Nguyen et al., 2018). To that end, an ongoing EU project, NextSkins (NextSkins, n.d.), brings together researchers from science, design and engineering, to collaboratively develop Living Regenerative Materials, composed of biomineralised biopolymers hosting bacterial spores. These materials are designed to be spatiotemporally programmed for a refined self-healing response in everyday consumer applications, such as helmets.

3 Methodology

We performed an exploratory review of literature and practice to gather example cases of microbial biomineralisation across art, product design, architecture, material science, and engineering. This review was performed from June 2023 to September 2023, screening the main databases in these relevant fields. The design venues screened include conferences such as Design Research Society (DRS) and the ACM Conference on Human Factors in Computing Systems (CHI), as well as journals, such as the International Journal of Design (IJD). The biology, material science and engineering venues reviewed include the journals such as Advanced Functional Materials, Nature Materials, and Cell Press. Due to the novelty of the topic, we supplemented this search with a review of online design magazines and blogs (e.g., Dezeen and Designboom), books (e.g., the Biodesign book by Myers (2012), and the Microbes I book, showcasing the student projects from Burg Giebichenstein University of Art and Design Halle (Gast, 2018)), and design awards and

exhibitions (e.g., BAD Awards, DDW). We used the following keywords for the collection of the example cases: *biomineralisation*, *biomineralised material*, *mineralisation*, *microbially induced calcite precipitation*, *MICP*, *calcium carbonate*, *biocementation*, *microorganism*, *microbial*, *microbes*, *bacterial*, *bacteria*, *S. pasteurii*, *cyanobacteria*, *materials*, *design*, *engineering*, *living materials*.

We ended up with 22 cases showcasing material outcomes where microbial biomineralisation is used as the primary biofabrication process for material formation (see Fig. 1 for the overview). Due to the novelty of this field, we have included all examples found without any filtering process; each case, despite sharing similarities, offers unique insights and nuances into the phenomenon. While we do not claim this list is exhaustive or complete, it highlights the most accessible cases of microbial biomineralization in the field. Among these examples, a few are relatively less realistic (or speculative), for example, the *Dune* project by Magnus Larsson (2010). We included these cases in our collection as they provide critical perspectives on the potential of microbial biomineralisation that are not evident in practical applications. Of the 22 cases analysed, one is a living artefact (*Self Healing Concrete* by Jonkers, 2007), and another suggests the use of bacterial biomineralisation in everyday settings through a self-production system (*Compact Chaff* by Cao & Beyer, 2017).

We analysed each case in terms of their material composition, fabrication and growing conditions and processes involved, as well as design purpose and outcomes (see Appendix of the overview visual of the analysis). This analysis, inspired by the ‘Material Benchmarking’ activity in the Material Driven Design (MDD) method (Karana et al., 2015), produced a rich overview and vocabulary intended to serve as a design space for novice biodesigners (presented in the coming section). Following this overview, our research team (the first, second, and last authors) further analysed these cases. We first considered the potential effect if the example case had resulted in a living artefact. Then, we examined their alignment with the five pillars of the framework by Karana et al. (2023) presented in the Introduction. Although all examples could potentially be further developed as living artefacts supporting all the pillars, we categorised each under the pillar we deemed most fitting. Finally, we selected two or three examples per pillar to illustrate distinctive directions microbial biomineralisation can be applied in living artefacts for regenerative ecologies. These examples are presented as design pathways in the Discussions section.



Fig. 1. 22 cases of material formation achieved through microbial biomineralisation.

4 Results

4.1 Organisms

The biomineralisation process in the analysed cases predominantly involves the bacteria *S. pasteurii*, in line with the scientific advancements discussed in Sect. 2. Exceptions include *Living Building Materials* (Heveran et al., 2020), *CyanoFabbrica* (Ferrari, 2021), and *3D Bioprinting of Mineralizing Cyanobacteria* (Reinhardt et al., 2023), which incorporate cyanobacteria in their processes. Only one case, *Self Healing Concrete* (Jonkers, 2007), explores *Bacillus* spp.

4.2 Material Compositions

The cases exhibit heterogeneous material compositions, with a prevailing use of fine sand substrates that afford sufficient inter-grain spaces for bacterial mobility (e.g., *Turbulent Casting* by Arnardottir et al., 2021). The strategic integration of biomineralising organisms, exemplified by *A Radical Means* (Palin, n.d.), *Biobrick* (Biomason, 2012) and *Dune* (Larsson, 2010), strengthens the sand substrate, creating a reinforced material where minerals act as binding agents. Beyond sand, a diverse array of materials is utilised, including concrete (*Self Healing Concrete* by Jonkers, 2007), gelatin (*Bac-toInk* by Hirsch et al., 2023), jute (*Calcified Column* by Beyer et al., 2019), and ground shells (*CyanoFabbrica* by Ferrari, 2021). Notably, *Co[w]work [1]*, *Co[w]work [2]* (Undritz & Wejda, 2017), and *Compact Chaff* (Cao & Beyer, 2017) utilise waste materials, like lignin, whey and chaff as substrates, emphasising sustainability and resource efficiency (Fig. 2). Each material imparts distinctive attributes to the biomineralised materials, contributing to the overall diversity and adaptability of the synthesised substances. In addition, *Lime Mycelium* by Strahl (2017) displays a collaborative interplay between living organisms, where mycelium symbiotically engages with biomineralising bacteria. Furthermore, *Biomineralized Cellulose* by Yu et al. (2021) introduces a composite material involving three distinct bacterial strains dedicated to bacterial cellulose production, PGA synthesis, and biomineralisation.



Fig. 2. The use of waste materials for microbial biomineralisation, two images on the left: *Compact Chaff* by Moyu Cao & Tony Beyer (2017) using chaff, and the image on the right *Co[w]work [1]* by Luis Undritz & Marc Wejda (2017) with the material whey (retrieved from: burg-halle.de).

4.3 Conditions and Media

The observed success in biomineralisation in the selected cases is closely associated with specific growth and biomineralisation conditions of the organisms involved, including temperature, nutrients, pH levels, and light exposure. Addressing this requirement involves for example the design of bioreactors, enabling the maintenance of optimal growing conditions and a consistent supply of essential nutrients, as seen in *Calcified Column* (Beyer et al., 2019) (Fig. 3, left and middle). Herein, the knitted textile containing bacteria was treated eight times over three days with urea and calcium chloride to keep the bacteria active and initiate the biomineralisation process. Likewise, In *Turbulent Casting* (Arnardottir et al., 2021) a diverse array of bioreactor prototypes has been developed, allowing for dynamic adjustments in nutrient/biomineralisation media composition, sand characteristics, mixing techniques, and the controlled application of heat and additional oxygen (Fig. 3, right). Additionally, the *Living Building Materials*

(Heveran et al., 2020) project incorporates temperature and humidity switches to enable regeneration, enhancing the material’s longevity and performance. Instead, in the *Dune* project (Larsson, 2010), the bacteria operate in a dynamic and open environment—the desert—where the designers speculate about varying salt levels and distribution of nutrients for either promoting bacterial clumping or ensuring even distribution of bacteria in the sand.



Fig. 3. Two images on the left: Calcified Column bioreactor, spraying nutrients on the knitted structure, by Bastian Beyer (2019) (retrieved from: dezeen.com), right: prototype of casting volumes of Turbulent Casting by Thora Arnardottir (2021).

4.4 Fabrication/Growing and Post-processing Techniques

The existing cases encompass a broad spectrum of making techniques. Among these techniques, moulding is the most prevalent, providing a structured environment for the wet material to take shape and dry, as exemplified in projects like *Biobrick* (Biomason, 2012), *A Radical Means* (Palin, n.d.), *Microbes Make Mountains* (Gonzalez, n.d.), *Mica Biofabrication* (Co-Lab – MICA Biofabrication, n.d.), and *Biomaterialized Cellulose* (Yu et al., 2021). Scaffold-based techniques, on the other hand, involve creating structures where bacteria can grow and induce biomineralisation, thereby reinforcing and toughening the structures. Projects such as *Calcified Column* (Beyer et al., 2019), *Porifera Mollusca* (Bade, 2017), and *Co[w]ork [2]* (Undritz & Wejda, 2017) utilise pre-made structures from various materials which are reinforced through biomineralisation by, for example, spraying bacteria to enhance structural strength. Furthermore, *Living Building Materials* (Heveran et al., 2020) uses a scaffold-based technique where photosynthetic microorganisms biomineralise inert sand-gelatin scaffolds (Fig. 4, left).

Moreover, advanced techniques like 3D printing have been employed in creating microbial biomineralised materials. Cases such as *BactoInk* (Hirsch et al., 2023) and *3D Bioprinting of Mineralizing Cyanobacteria* (Reinhardt et al., 2023) demonstrate the possibility of printing living hydrogels layer by layer, offering innovative avenues for precision and customisation in material formation (Fig. 4, right).

In some cases, post-processing techniques have been used to further enhance the material as seen in *Marmelstein* (Herbert, 2017) where they took *Biobrick* (Biomason, 2012) as a starting point and used etching with acetic acid to decompose the limestone, showcasing another innovative approach to material processing which allowed customised manufacturing (Fig. 4, middle).



Fig. 4. Left: Sand and a gelatine-based hydrogel mixture in a mould where bacteria are added to create Living Building Material by Heveran, et al. (2020), (retrieved from: colorado.edu), Middle: undercuts and organic shapes inside of a brick in Marmelstein by Paulina Gellert & Anna Herbert (2017) (retrieved from: burg-halle.de), Right: 3D printed bacteria-containing microgel-based ink before the microbial biom mineralisation process of BactoInk by Hirsch, et al. (2023).

4.5 Material Performances and Application Areas

The cases exhibit a rich assortment of properties across technical, environmental, and experiential dimensions. From a technical standpoint, these materials demonstrate remarkable mechanical properties (as discussed in Sect. 2), offering sturdy and stable structures while also displaying a captivating lightweight composition, as highlighted in *BactoInk* (Hirsch et al., 2023), *Biom mineralized Cellulose* (Yu et al., 2021), and *Porifera Mollusca* (Bade, 2017). The self-healing property of biom mineralised materials is showcased in *Self Healing Concrete* (Jonkers, 2007) and *Calcified Column* (Beyer et al., 2019). In *Biobrick* (Biomason, 2012) and *Living Building Materials* (Heveran et al., 2020), designers use their material for post-use recycling. Furthermore, biodegradability and compostability are emphasised in *Lime Mycelium* (Strahl, 2017) and *Porifera Mollusca* (Bade, 2017), facilitated by mycelium and sponge. Additionally, the low carbon footprint of the process due to lower temperatures used in fabrication is highlighted in *A Radical Means* (Palin, n.d.).

The versatility of biom mineralised materials spans diverse application areas in the analysed cases. They can be used in the construction and building materials sector, as exemplified by *Self Healing Concrete* (Jonkers, 2007), *Living Building Materials* (Heveran et al., 2020) and *Biobrick* (Biomason, 2012). Beyond construction, biom mineralised materials were used in everyday consumer products, including furniture, in *A Radical Means* (Palin, n.d.), or wearables like sunglasses, as seen in *CyanoFabbrica* (Ferrari, 2021). Furthermore, *Compact Chaff* (Cao & Beyer, 2017) is a tool designed for people to use the process of biom mineralisation to create materials with chaff. In *Marmelstein* (Herbert, 2017) designers envisioned applications like flexible rack systems and integrated wall hooks. The *Fossil Identities* case (Wienkamp & Treutner, 2017) exemplifies the creation of intricate jewellery pieces, showcasing the durability and aesthetic appeal of biom mineralised materials. This aesthetic is also reflected in other art objects and installations such as *Microbes Make Mountains* (Gonzalez, n.d.), to raise awareness for designing with microorganisms (Fig. 5, left).

Furthermore, *Mica Biofabrication* (Co-Lab – MICA Biofabrication, n.d.) demonstrates the use of biom mineralised materials to create artificial reefs for oysters, contributing to marine ecosystem restoration efforts (Fig. 5, middle). The company *Bind-Tech*

(Bind-X, 2013) showcases products for customised dust control and weed management, leveraging biomineralisation for sustainable land management practices. In the realm of health and nutrition, biomineralised materials demonstrate significant potential. The *Subliminals* (Wagner, 2017) project suggests innovative uses in the food industry with growing minerals for nutrients (Fig. 5, right). Furthermore, the repair of mineral-based materials, such as bones, indicates future applications in medical fields, enhancing bone repair and regeneration through biomineralisation processes, as mentioned in *BactoInk* (Hirsch et al., 2023).

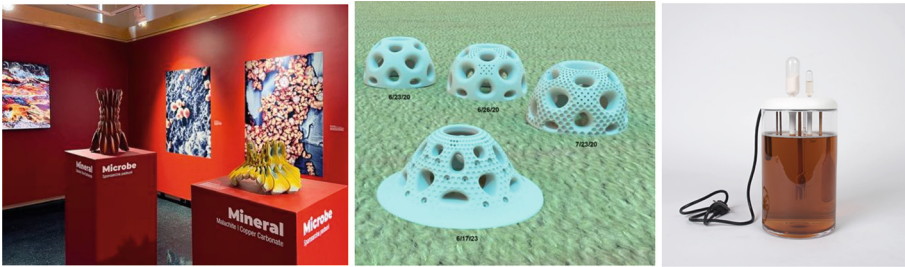


Fig. 5. Left: Laura Maria Gonzalez’s exhibition *Microbes Make Mountains* with two prototype sculptures and SEM images (retrieved from: (Gonzalez, n.d.)), middle: Mica Biofabrication by Co-lab 3D rendering of habitat structures for oyster reefs in the sea (retrieved from: mica.bio), bottom right: *Subliminals* by Andreas Wagner (2017), growing minerals with objects inside a glass containing nutrients (retrieved from: burg-halle.de).

5 Discussions: Design Pathways for Microbial Biomineralisation

The conceptual framework delineating five fundamental pillars by Karana et al. (2023), serves as a foundational structure for identifying future design pathways for microbial biomineralisation to support regenerative ecologies. We provide two or three examples from the collected cases to articulate these pathways.

5.1 Microbial Biomineralisation in Living Artefacts for Cyclical Material and Energy Systems

Microbial biomineralisation in living artefacts can support cyclical material and energy systems, as illustrated by the cases discussed. We speculate on two main approaches. Firstly, a living artefact can utilise the self-healing capability of microbial biomineralization (as seen in *Self-Healing Concrete*) to extend life cycles in everyday consumer products like helmets or electronic cases, as envisioned in the *NextSkins* project mentioned earlier. Secondly, if biomineralisation is achieved through photosynthetic cyanobacteria, as in the example of *3D Bioprinting of Mineralizing Cyanobacteria*, the living artefact can potentially contribute to purify the air or generate electricity while self-healing or forming new material structures.

5.2 Microbial Biomineralisation in Living Artefacts for Biodiversity

Microbial biomineralisation in living artefacts can stimulate biodiversity and symbiotic relationships between biological systems manifested as multispecies ecosystems. For instance, in the example case *Bind-Tech*, microbial biomineralisation restores soil ecosystems by increasing soil strength and protection. Moreover, such living artefacts can be used as bioreceptive structures, such as in the case of *Mica Biofabrication*. When these artefacts remain alive in use time, they may continuously multiply their bioreceptive and restorative effects over time and scale, promoting ecosystem growth and stability.

5.3 Microbial Biomineralisation in Living Artefacts for More-Than-Human Sensibilities

Living artefacts utilising microbial biomineralisation offer a unique opportunity to foster mutual and interdependent relationships between humans and other living organisms. For instance, microbial biomineralisation can be activated by specific human actions and perpetuated through care practices. Additionally, the production of biomineralised materials can be designed to be more noticeable to people. This approach can be applied to growing artefacts for everyday use, such as furniture pieces that users cultivate by applying bacteria and nutrients to textile structures, as demonstrated in the *Calcified Column*. This approach can also extend to personal artefacts that evolve over time through interaction with the human body, like jewellery seen in *Fossil Identities*. These dynamic pieces then not only serve functional purposes but also help individuals become more attuned to and appreciative of the unique temporalities, scales, expressions—and needs—of the microbes involved. Another example is Thora Arnardottir's *Turbulent Casting*, which proposes a new approach to form-finding called bacterial sculpting. Although it is not intended as an everyday artefact by the designer, the method presented involves a collaborative process between humans and microbes in material creation, potentially altering how designers understand organism and their agency in design through an intimate process of sculpting. Future living artefacts can be developed with the same mindset to assist hobbyist sculptors in creating sculptures with living media, fostering a deeper connection with other life forms.

5.4 Microbial Biomineralisation in Living Artefacts for Ecological Literacy

Living artefacts utilising microbial biomineralisation can enhance awareness and understanding of essential ecological principles such as photosynthesis, nutrient cycles, metabolic intricacies of the species involved, and the complex interrelationships between multiple species in ecosystems. For instance, a living artefact can demonstrate the intricate nutrient and energy exchange between two species of microbes during the microbial biomineralisation process, as seen in *Lime Mycelium*. Additionally, showcasing the capacity of the biomineralisation process to utilise waste streams as a resource for creating new materials or self-healing, as demonstrated in *Co[w]work [1] and [2]*, can deepen comprehension of these complex metabolic processes.

5.5 Microbial Biomineralisation in Living Artefacts for Culture Change and Holistic Worldviews

Living artefacts utilising microbial biomineralisation can catalyse a transformative cultural shift towards more sustainable futures, inspiring communities to rethink the impact of their actions on ecosystems, and explore alternative ways of making and living. A notable example is the project *Dune*, which employs biomineralisation to create accommodations within desert landscapes. Inhabiting constructions derived through this process, can foster alternative ways of communal living and promoting new aesthetic judgements based on the unpredictability inherent in living systems. Additionally, democratising access to the biomineralisation process by offering hands-on experiences, as demonstrated in *Compact Chaff*, challenges societal stigmas associated with waste resources and bacteria. This project shows that waste and bacteria can be transformed into valuable materials, encouraging a reassessment of what is considered waste or valuable. By showcasing the creative and constructive potential of these often-overlooked—even despised—resources, *Compact Chaff* promotes a more inclusive and sustainable approach to resource utilisation.

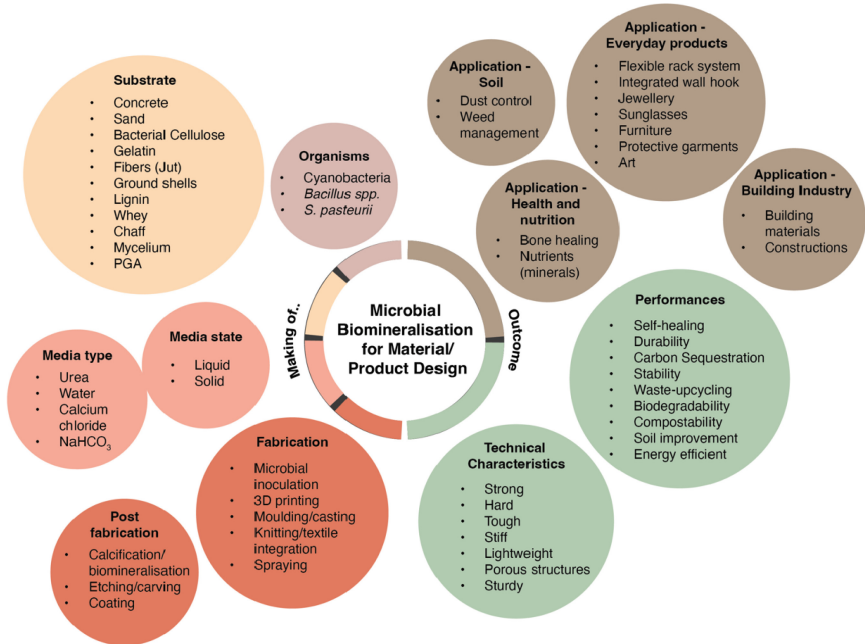
6 Conclusion

This paper has explored the transformative potential of microbial biomineralisation in the design of living artefacts aimed at supporting regenerative ecologies. We unpack the notion of microbial biomineralisation for design, illustrating how—by harnessing the ability of microorganisms to drive mineral formation—it can create materials with exceptional properties and remain alive during the use time of a material. Our review of existing cases across diverse fields offers a vocabulary and delineates a design space that can be utilised by biodesigners to understand and integrate microbial biomineralisation into their work. Finally, we speculate on the implication of these cases when the organisms are kept alive in the everyday use of these artefacts. We propose pathways to bridge microbial biomineralisation to regenerative ecologies through these artefacts.

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Appendix

Overview Analysis Diagram of Microbial Biomineralisation for Material/Product Design of the 22 Cases



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