A Review of Biofabricaton in Design Innovation Field

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ABSTRACT

Since industrialization, human has fabricated a tremendous amount of product and, at the same time, caused countless irreversible impacts on the planet. Artists and designers have called for changes since 1960. In recent decades, product designers have started to get involved in the rethink of fabrication and production. With advancements in biotechnology and material science, more and more possible solutions to replacing petroleum-based products have come forth. Consequently, the biomaterial is one of the noticeable developments, and biofabrication has become an emerging field. This paper aims to give an overview of the current literature on biofabrication from the perspective of design and innovation. Three aspects of practical factors entailed were found to be the characteristics of the organism, methods and tools to fabricate and the considerations for developing biofabricated products. Besides the elements that need to be taken into account, potential values that the biofabrication movement can bring out were found to fall into three levels— ecological/biological, ethos/social and experiential/sensorial. To tackle the difficulties in designing a suitable biofabricated outcome to achieve genuine sustainability, the capability of designers to combine these factors and values is essential and worth further development.

LAYMAN'S SUMMARY

Biofabrication is a way of production involving any part of biological organisms, initially referring to tissue engineering in biomedical science. Because biofabrication has a cross-disciplinary feature and the knowledge in biotechnology is increasing, the concept and technique are gradually applied in other fields. Pioneers in sustainable design have seen its potential in expanding the possibilities and then dived into researching specific materials– biomaterials. Besides the scientific academia, designers have also used it to develop products further. It combines standard design tools and organisms that can be grown accumulatively. Designers have met multiple challenges in this fresh approach, especially when it confronts designers' custom and when product development is the intention. To deal with this problem, the values brought out by biofabrication are proposed to be understood and contemplated more, especially those hidden behind the environmental index, for instance, their original characteristics designed by Nature, the connectivity with society and human needs that trigger consumers' activity. By further diving deep into the integration, designers can exert their influence and create meaningful embodiments that contribute to sustainability in a broader context.

INTRODUCTION

'One of the three or four most decisive transitions in the history of humankind, potentially of similar importance in the history of the Earth itself, was the onset of industrialization' (Crutzen, 2007)

Industrialization has brought the world a firmly fixed mindset and manufacturing processes that emphasize efficiency the most. The industry follows the standardization of centralized production and pursues the market profit as much as possible without considering other aspects, and this phenomenon leads to significant environmental costs (Andréen & Goidea, 2022). With the global population rapidly growing, consumption is inevitably increasing, and natural resources are consumed more than they can regenerate (Collet, 2021). According to EU Retail Forum for Sustainability, the textile and construction industries are the third and fourth 'in the ranking of a product category which causes the greatest environmental impact'. In this context, the design profession, which emerges with the industrial revolution, has started to rethink the role and responsibility of designers (Collet, 2021). The shift from conventional manufacturing procedure entails a systemic change which exerts a broader influence from the mental model. Therefore, design plays an important role here since it influences our daily consumption in concrete and abstract aspects.

As expressions of critical thinking, art and design always stand at the front of the era to push human culture forward. Before real improvements in design production start to get involved in this movement, artists and speculative designers have called for change on 'the alienation of human activity from nature' and the 'necessary transition from anthropocentrism to biocentrism and ecocentrism (Melkozernov & Sorensen, 2021). From 1960-1980, eco-art impacted society by arousing awareness of irreversible environmental problems. This ecological alarmism can be considered the ancestor of bio-art, which expands the eco-art by including more versatile interpretations, media and imaginations from the biosphere and nature (Melkozernov & Sorensen, 2021). More than raising awareness, biodesign emphasizes the physical integration of organisms. It 'goes further than other biology-inspired approaches to design' and 'refers specifically to the incorporation of living organisms or ecosystems as essential components, enhancing the function of the finished work' (Myers, 2018).

Several approaches arise in the context of combining biology and design. Camere and Karana have grouped them into four categories. 'Augmented biology' attempts to design biological organisms based on biotechnology techniques. By employing re-engineering cells, designers explore more possibilities to tackle contemporary problems in the world. Similarly, designers that work on 'biodesign fiction' envision the future with biotechnologies. The speculative outcomes aim at provoking people to rethink the current situation and interact with the possible future. In terms of fabrication in the design field, 'Growing Design' and 'digital biofabrication' are approaches characterized by incorporating common design and biological means and are less specific to biotechnology (Camera et al., 2018). The combination of biology and design appeals to more and more attention because of its tangibility and function from a design perspective. In this new design practice trend, the Do-it-yourself biology (DIYbio) approach also gives a crucial function. Although the designer's DIY approach seldom becomes to lead the companies in this industry, there is no doubt that 'the case studies of biofabricated materials were initially experimental and related to speculative design' (Camocini & Vergani, 2021). Gradually, biofabrication becomes a more solid subject in the cross-disciplinary collaboration of biology and design.

A transdisciplinary understanding is essential to make this new form of design practice contribute to a shift towards the new era. Hence, this literature review focuses on considerations of biofabrication in the design and innovation field instead of diving into the technical details from the biotechnology and science perspectives. By exploring biofabrication specifically, the following steps toward a bioeconomy and a more open society can be extended and achieved.

Research Question

Based on the background of biofabrication development, this literature review aims to answer the following research questions:

- What factors are considered in biofabrication from the **designers**' perspective?
- What values do '**bio' elements** bring to the new paradigm of fabrication?

The first question would be answered in the first session - **Practical factors entailed in biofabrication**. The third session brought out the second question: **Values emerged from the biofabrication movement**. This review aims to respond to the research questions based on current literature, mainly in the design and innovation field.

METHODOLOGY

The literature research was conducted via several search engines under the Utrecht University Library system. First, the bibliographic database Scopus, which indexes over 21,000 scientific journals, was chosen. Second, Web of Science was used to find more articles with different perspectives since it offers Social Sciences Citation Index (SSCI) and Arts & Humanities Citation Index (A&HCI), other than the Sciences Citation Index Expanded (SCI). Last, numerous articles were found in Google Scholar, which has 'an index of over 50 million articles, books, dissertations and patents covering all subjects' (Utrecht University Library).

The topic of this literature review covers biology and design innovation. However, since the terminology 'biofabrication' was coined in the biomedical field, most of the articles found were not related to the intended issues, even though multiple keywords were used. Therefore, the Snowball method was adopted as the first step, which suggests 'a search on the basis of a suitable publication you have found earlier' (Utrecht University Library). Next, based on the Systematic method, as much literature related to 'biofabrication' as possible was searched and then was limited by adding 'NOT 'operators (Table 1).

Table 1: Overview of search terms and the results.

	Search engine	Search term	Filter	Amounts of results
01	Scopus	biofabrication AND design	-	459
02	Scopus	biofabrication AND design	Subject area limited to Materials Science, Multidisciplinary, Environmental Science, Agricultural and Biological Sciences, Arts and Humanities	254

03	Scopus	biofabrication AND design	Subject area limited to Multidisciplinary, Environmental Science, Agricultural and Biological Sciences, Arts and Humanities	17 (only 1 related)
04	Scopus	biofabrication AND design	Subject area limited to Multidisciplinary, Arts and Humanities	7 (only 1 related)
05	Scopus	biofabrication AND design	Subject area limited to Arts and Humanities	1
06	Scopus		Author includes “Collet, Carole”	6
07	Web of Science	design innovation (Topic) AND biofabrication(Title)	-	2 (biome dical)
08	Web of Science	design (Topic) AND biofabrication(Title)	-	106
09	Web of Science	design (Topic) AND biofabrication (Title) NOT tissue (AllFields)	-	29
10	Google Scholar	biofabrication biodesign	-	1290
11	Google Scholar	biofabrication-cells -tissue -engineering -medical -healthcare -nanoparticles-hydrogel -organ	after 2018	357

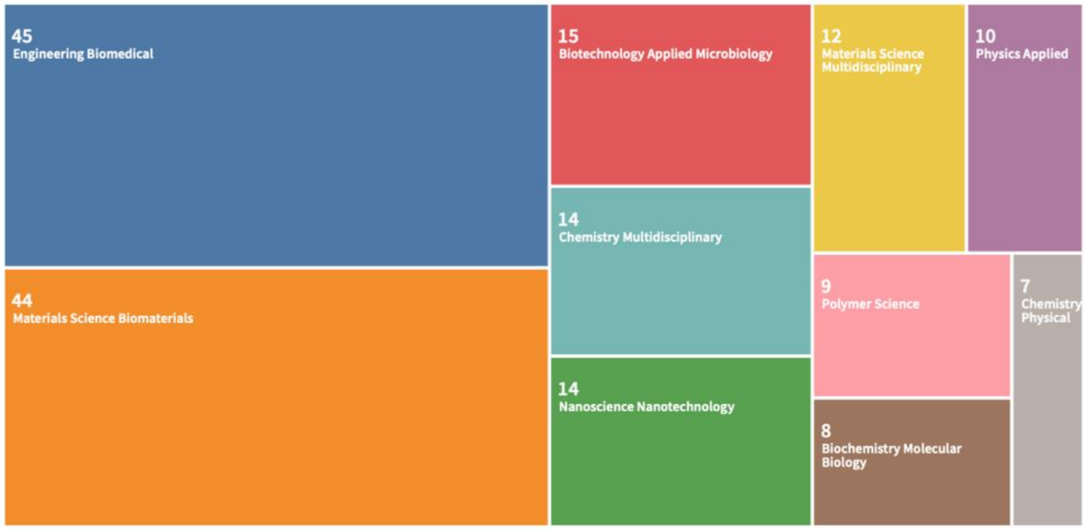

Figure 1: A filed distribution of 106 publications searched in the eighth round. The areas on the chart are not strictly proportional to the values. (Web of Science - Analyse Results)

Only one suitable article was found in the database Scopus. Hence, an expanded search on a particular author was conducted in the next round. Then, another keyword that the article used - 'biodesign' was added to the search terms in Google Scholar. In the end, 357 articles were found after limiting several keywords that are commonly used in biomedical engineering, healthcare, and nanomaterial sciences fields. Since only two articles in the first ten results were helpful, only the first 60 articles from Google Scholar and 29 from Web of Science and 357 were analysed.

Practical factors entailed in the biofabrication process

This section presents three main description categories that articulate the concrete process of biofabrication. The material type is the first focal point since particular organisms are specifically targeted in the biofabrication field. This basic viewing framework can make understanding biofabrication more at ease. Next, fabrication approaches collect a rich array of biofabrication-related methods and tools used in general and on the designer's table. To figure out how design is involved in this emerging field, as emphasized in the Introduction chapter, a perspective from designers is focused here rather than the industry or academia. Last, considerations for developing reveal several concerns that challenge designers in the process and the support that designers can contribute to the biofabrication practice.

Material origins

The diversity of organisms brings tremendous possibilities for biological application in human history. Easily accessible natural materials like wood and plants have been utilized in various aspects. In the last decade, the majority of emerging biofabrication materials used in design projects were derived from three groups of life forms: fungi, bacteria and algae (Camare et al., 2018).

Amadou, also known as German felt, is an early fungal material developed spanning thousand years. The distinct fruiting bodies produced by *Fomes fomentarius* and *Phellinus ellipsoideus* inform humans of the potential of transforming fungal macrostructure into materials. Soft and felt-like materials were then made from the fibrous trama, the fleshy part of the inner side of the mushroom (Gandia et al., 2021). Besides the polypore basidiocarps, mycelium has become the most promising element in fungi-derived materials. This vegetative part of a fungus is composed of natural polymers such as chitin and β-glucans that result in fibrous properties (Appels et al., 2019). Mycelium packaging grown on agricultural waste was one of the first few experiments that applied it in the design field. Material properties like insulation, shock-sorbing and light-weight make it suitable for replacing polystyrene and other synthetic materials used in packaging, helmets and panels, which are specific focuses in product design (Camocini & Vergani, 2021). In addition, the diverse forms of fungi caused by different cultivation ways bring more possibilities to the fashion and architecture sectors. For instance, leather-like substitutes are fabricated from fungal pellets cultured in liquid (Jones et al., 2021).

Bacteria have been widely applied in fermentation. In recent decades, applications involving genetic modification have been taking the trend due to the easy-growing and high-replicating characteristics of bacteria (D'Olive & Karana, 2021). For instance, fashion design pays a lot of attention to bacterial pigment and cellulose fibres. The cellulose layer produced by bacteria is flexible and thus suitable for moulding, which is different from the traditional fibres derived from plants. *Xylinum* is a project developed by Jannis Hülsen and Stefan Schwabe, aiming at growing products with *Acetobacter xylinum*. This project combined 3D production techniques to shape the objects directly and tried to balance the industrial need and the biological characteristics (Camere & Karana, 2017). Algae have been utilized in the energy field as promising bioresources. Due to their rapid and massive growth, algae are considered almost inexhaustible and renewable resources. Seaweed is relatively used as a biofabrication material than microalgae for designers owing to its accessibility. Potential algae applications include textiles pigments, algae-blend foams and air purifier biofilms (Camere et al., 2018; D'Olive and Karana, 2021).

Fabrication ways

Growing Design is a term peculiarly used to represent the design development in physical biofabrication (Camere & Karana, 2017). More practical application and hands-on action are emphasized to achieve the goal of product design. Similar steps are taken in the design process: preparation, growing, drying and shaping (Camera et al., 2018). The first two phases are set for letting the organism fabricate the material, and the last two phases turn the outcome into actual materials that designers can work on. In the case of fungal materials, liquid-state fermentation, liquid-state surface fermentation, and solid-state fermentation are the modern methods of fabricating. At the same time, wild basidiocarp foraging is adopted in early times to make functional materials (Gandia et al., 2021). Solid-state fermentation mainly produces fungal foams and leather-like materials, and liquid-state (surface) fermentation methods are associated with making paper-like materials (Gandia et al., 2021). Mostly, mycelium-based composite and pure mycelium are the fabrication results, and designers manufacture them by typical processes, such as laser-cutting, CNC cutting and milling. As more and more designers look into fungi-derived materials, the fabrication focus is moved to numerous parameters besides the post-processing and broader scales from nano to macro involved in the biological process

(Goidea et al., 2022). Likewise, the process of growing bacteria cellulose starts from the culture in a nutrient medium with optimal conditions. Static cultivation is more famous for the product design field since more extensive materials are allowed to produce in this case (Camere & Karana, 2017).

Moreover, designers need to consider changeable material properties after drying, such as colour, thickness and texture, since the obtained material has high water content and a distinct appearance. Since bacterial cellulose is flexible and applied to fashion design popularly, blow-moulding and sewing are introduced to manufacturing afterwards (Camere & Karana, 2017). Indoor micro-algae culture also applies to the above steps regarding growing and harvesting, while macro-algae is preferable by designers (Camere et al., 2018). Like wild basidiocarp foraging, macro-algae need to be collected from seashores and processed further. Therefore, the DIYbio approach, also the origin of Growing Design, is suitable for algal materials on the design site (Fuentes et al., 2020; Camere et al., 2018). However, this limits the potential of product design since designers are accustomed to observing and interacting with materials to seek in-depth insights and opportunities. Hence, several designers are eager to develop an effective indoor system to cooperate with algae (Camere & Karana, 2017).

Digital biofabrication allows designers to fabricate biomaterials with less biology-dominated sense, and technology tools play an equally essential role here. Zhou et al. have categorized three main pillars in the taxonomy of digital tools related to biofabrication and biodesign. The second pillar, embodying the habitat, is the middle phase of the biodesign as they framed, and the most associated one with the biofabrication process. Digital tools are introduced in manufacturing to make the embodiment more precise, such as using 3D bioprinting techniques to extrude biomaterials. With the enhancement of precision, more possibilities are developed to support the biofabrication that involves living organisms. For instance, the installation in project *H.O.R.T.U.S XL* was printed through the bioFDM (Fused Deposition Modeling) process, and micro-algae were inoculated into the scaffold with a specific gel medium (Zhou et al., 2022; Goidea et al., 2022). Furthermore, the form of this significant artefact was built based on collective coral morphogenesis (Zhou et al., 2022). Here, another aspect that digital tools can contribute to biofabrication comes in. Before the manufacturing process, form-finding tools like biologically informed computer-aided design (bioCAD) tools can study the characteristics of a natural place in terms of physical, biological and ecological aspects (Zhou et al., 2022). This help to guide biofabrication, especially in architecture, towards a scale that focuses not only on materials but also on habitat. Parametric design tools like Rhino-grasshopper software also generate the structure (Zhou et al., 2020). With the increased involvement of living artefacts, digital tools under the other two pillars, understanding the habitat and perpetuating the habitat, will become more critical in the foreseeable biofabrication future (Karana et al., 2020; Zhou et al., 2022).

Design considerations

No matter which material and manufacturing approach is chosen, the design of a physical object shares the same manner of development. Several difficulties in biofabrication need to be explicitly tackled from the designers' perspective. Above all, biological factors' involvement considerably affects how designers usually work. Unlike researchers in a biology laboratory and industry following a strict and preset procedure and seeing organisms as the experiment's common material, designers primarily rely on the continuing tinkering activity in the process to understand the materiality and prefer to play with a palette of materials rather than stick to one material (Camere & Karana, 2017). Moreover, Growing Designers commonly perceive this practice as co-performing and are more aware of their relationship with the organisms (Camere et al., 2018). However, subtle effects caused by tinkering are hard to observe and therefore inform designers less than they usually need. At the same time, the activity alters the growth in an unexplainable way and makes the outcome unpredictable. These factors all influence the intentionality of designers and break the design sensibility they initially depend on (Camere & Karana, 2017; Camere et al., 2018).

Secondly, as biofabrication has a hidden aim to develop products, common considerations involved in the later stage of innovation also need to be considered. The fabrication period is already a concern during the design process because the delay in time 'separates the moment of crafting from the evaluation of the outcome' (Camera and Karana, 2017). Moreover, it is adverse to the current industrial need for linear and urgent production, especially in construction cases (Andreén et al., 2022). Another essential element in feasibility is the life cycle of the product. Except for the biomaterials that are under improvement towards higher durability, most materials that designers can access are sensitive to water and highly perishable. That is to say, if designers only apply the grown materials on standard consumer products as they are used to, the shortened lifetime of usage is a downside and 'makes us produce and dispose of more' (Camera et al., 2018). Especially when designers adopt the material-driven approach, the limitations and boundaries of the material are usually unknown in the beginning because the method counts on the interrelationship between humans and materials in the process (Barati, Karana, & Hekkert, 2015). Furthermore, the appearance and concept of these newly emerging materials still need intelligent ways to communicate with the general public. Regarding the 'established sociocultural meanings of fungi as dirty and unhealthy' (Karana et al., 2018), materials framing is now a focus in the biofabrication field since gaining acceptance from the public can be a long way to go (D'Olivo & Karana, 2020). The position of biomaterial, showing newness or used as a surrogate material, also affects the development towards bio-based products (Karana et al., 2018). These are all practical factors designers must consider when creating a biofabricated possibility.

Based on an interview study of several designers that own years of related expertise, Growing Design is associated with visions of 1) cleaner production; 2) consumer appreciation and awareness; and 3) a reinterpretation of Nature (Camere et al., 2018). In like manner, three central values that biofabrication can bring are introduced in the next chapter.

Values emerged from the biofabrication movement

This section elucidates three valuable qualities interweaving the emergence of biofabrication in a design sense. Above all, ecological value is the most emphasized aspect in all sorts of biomaterial-related statements. However, a similar but independent argument regarding the significance of adopting biological intellection has yet to be brought up extensively. Herein, contemplations in architecture are shown to embody the importance of incorporating biological principles since it is a design category that has to consider scales, agents and elements from a broad and integrated lens. At the same time, correlated values from the social side become much more visible because habitation discloses how communities live out and interact with the environment. Last but not least, fresh experience in the senses is one of the drives that prompt humans to keep concretizing ideas and values. Nowadays, the experience that can remind us of living with and within Nature is even more highlighted in this era of the pandemic, artificial intelligence and war.

Ecological and biological values

Ecological values brought by biomaterials have been discussed and researched in depth in the literature of sustainability and biomaterial science fields. This review, based on articles in design and innovation, will exclude this part and focus on other merit mentioned less when it comes to biofabrication. However, it is still worth being pointed out here with an associated topic, biological values. The trend of incorporating biology language in design is growing along with the spread of the biomimicry spirit. Nature informs us of sustainable ways to fabricate. As a consequence, designers start to seek inspiration at all levels from organisms, including the material, shape, behaviour, function and pattern. As a design educationalist, Collet started to implement biology in his educational method for sustainable design in 2007. According to his on-site observation, many designers tried to incorporate biological principles in their design due to sustainable ambitions, while some just applied them because of their freshness (Collet, 2021). However, besides the factual knowledge we can learn from Nature, the inherent wisdom is what we need to contemplate and apply to design to gradually achieve a more authentic biofabrication.

Andréen and Goidea have argued four principles for successfully implementing biology in construction. As architecture is an applied design that considers numerous practical factors, the incorporation of organisms not just looks potential but poses a huge challenge in this discipline due to inherent conflicts between the organism's needs and the construction requirements (Andréen & Goidea, 2022). Based on the experience of biofabricating an architectural prototype Protomycokion, they proposed diversity, complexity and specificity, durability through resilience, and feedback and adaption as central principles for constructions in this new paradigm. First of all, diversity is a prominent feature of the biological world. Andréen and Goidea claimed that the variety of organisms has the potential to create diverse architecture types. To elucidate if biomaterials are becoming an adequate solution, a library of the organism and material variations can be researched and designed to satisfy numerous unique needs. Furthermore, the local contexts will be highly emphasized since the regional plantation and waste streams relate to resource availability. In this way, the current situation of using standardized and centralized construction materials can be adjusted. In the future, dynamic performance exhibited by the materials, probably living organisms, can also be expected around our living space. Secondly, the value of complexity and specificity can be exerted, especially with the assistance of digital fabrication. In the case of Protomycokion, the algorithm arranges the interstitial spaces and assists in constructing the network of channels by considering the frequent curvature, interconnections, and multi-directionality. This embodied the complexity in the design outcome by achieving 'the nonlinear interdependence of such systems, unlocking functional integration and high degrees of optimization' (Andréen & Goidea, 2022). At the same time, it considers the organism's need since the fungus inside requires sufficient surface area and oxygen supply. The specific form, encoded processes and relationship between the biological agents and the materials can be carried out with the computational design, and the results can further influence the complexity (Andréen & Goidea, 2022). Thirdly, durability through resilience refers to how biological design systems use the material. Like the biological bodies remaining in their form while specific cells perish, resilience in the complex system represents the ability to re-organize under disturbances and stay functional. In contrast, engineering resilience emphasizes change resistance and structure conservation (Andréen & Goidea, 2022). The flexibility and recyclability of biomaterials and the dynamic characteristics of living organisms in the biofabricated structure can concretize this value. Last, feedback and adaption are proposed in the built environment with great emphasis on inhabitation. Compared with primary construction materials, biofabrication shows a disadvantage in efficiency. However, building construction under a slow and interactive process is preferred in a more organic and fluid model to enable adaptivity (Andréen & Goidea, 2022). Overall, these four principles present the biological values by using the downsides of biofabrication, which are advantages in the biological world with a nonlinear mindset. They are all just typical and neutral features in Nature, yet the biofabrication movement exhibits them to the world with biomaterial's affordance in a more modern and concrete way.

Ethos and social values

With more and more scientists, designers and entrepreneurs devoting themselves to research and commercial attempts, the biofabrication movement underlines the spirit of this era. The most important one is the rethink and reinterpretation of the natural ecosystem (Camocini & Vergani, 2021). Throughout history, humans have adopted a dominative view of the environment and transformed it to 'adapt' to human activities (Collet, 2021). After the emergence of system thinking, 'the Zeitgeist of the early twenty-first century is being shaped by a profound change of paradigms, characterized by a shift of metaphors from the world as a machine to the world as a network' (Capra & Luisi, 2014). Visible environmental issues have caused humans to face the environmental consequences under the iceberg we have made for uncountable years. With the unravelling of complex puzzles and the continuing efforts to communicate, the general public has progressively aroused sustainable consciousness. However, as long as the way we utilize resources on the Earth stays similar, we would still 'alter the planet's geophysical forces, unbalance its ecosystem and initiate a climate change when we begin to industrialize our means of production', according to Nobel Laureate Paul Crutzen. The responsibility of design is then called for engaging in the transformation.

Although more sustainable practices are applied, and a circular economy mindset is gradually taken into account nowadays, making products and consumerism are still causing environmental consequences (Collet, 2021). Besides seeing the world as a network, the reconnection of societies to the biosphere becomes an urgent need. 'The human brain evolved in a biocentric world, not a machine-regulated world, and thus to achieve the full potential, humanity should not be isolated from the natural world' (Wilson, 1984; Kellert & Wilson, 1993). The biofabrication movement can assist the integrated view of being part of the biosphere. Besides the biological spirit that can contribute to the design itself, as stated in the last section, merging the vision of post-Anthropocene in the embodiment also helps to spread the importance of considering non-human agents in human activities (Camocini & Vergani, 2021). Owing to the continuous reflection upon the design process and outcome, designers have kept fostering themselves to break through the original framework limited by the industrial age. Biofabrication is not just a manufacturing approach but also a process for the designer and the public to re-examine 'the wellbeing of the ecological system as a whole' (Camocini & Vergani, 2021).

One of the design approaches in biofabrication that intervenes the society is the DIY-bio movement. It influences the community by democratizing life sciences and biotechnology (Camocini & Vergani, 2021). As a result of the push from the maker movement and open science, DIY-bio combines their spirit and tools and expand the public's accessibility and imagination to biological elements and reconnect with nature in a modern and physical way (Melkozernov & Sorensen, 2021). Although DIY-bio projects seldom come to realize in a commercial place, they have contributed to developing a more sustainable society. The unseen merit has shown in the biofabrication practice in remote territories, for example, Puerto Williams in Chile. As one of the most southern places on the planet, the territory eagers to establish production chains locally and self-sufficiently, especially with biomaterials (Fuentes et al., 2020). These areas own abundant natural resources while lacking technological equipment. Consequently, open-source protocols are required to achieve material sovereignty. In this case, knowledgeable understandings of the natural environment are crucial to further biofabricate with local materials, and accessibility to information and basic infrastructure is necessary (Fuentes et al., 2020). Herein, DIY-bio can offer more bottom-up and varied ways because designers and enthusiasts have also tried to develop their ideas under the circumstances of scarce resources. DIY-bio brings value to the remote territory, and at the same time, the local society can create value for the biofabrication movement.

Experiential and sensorial values

Equally important as the values that biofabrication brings to the environment and the era, the experiential influence is fundamental because it greatly determines how and how people adopt and embrace biofabricated objects (Karana et al., 2018). According to Bruner and Kumar, the hedonic aspect of the product is sometimes more important than the utilitarian side in terms of adoption and acceptance. In other words, sensations constitute a vast part of human activities and drive our commercial productions. As the central element in biofabrication, biomaterial already provides conspicuous characteristics that appeal to newcomers. However, the sense of freshness has expired, and the experience offered by materials is worth exploring more.

As the medium for communicating with users, the material can deliver four experiential levels— sensorial, interpretive, affective, and performative (D'Olive & Karana, 2021). By shaping these material properties, designers can 'influence social and cultural practices related to consumption' (Giaccardi & Karana, 2015). However, the experiences provided by current biofabricated objects are still limited by their insufficient development. According to an acceptance test evaluated by non-designers, the mycelium-based products they investigated majorly presented naturalness owing to their appearance and the brittle property (Karana et al., 2018). Recently, Material Driven Design (MDD) method is a step-by-step approach for creating meaningful material experiences that have been applied in several biomaterial design projects (Karana et al., 2018). With a materials experience vision in mind, more possibilities can be explored and further influence consumerism. In comparison with biomaterials, the biofabrication process provides more unexpected experiences. An interview study of experienced designers revealed that 'designers experience a mixture of awe and amazement through the process of growing a material, in which making happens beyond their intervention, and because of another form of life participating in the process' (Camere et al., 2018). The importance lies in the intimate relationship designers have built with the material through the growing process. This unexpected interaction has created an affective bond that makes designers' attribute higher value to the materials as they grow' and 'inspires them to seek a change in social practices of consumption by capitalizing on these novel fabrication processes to increase people's appreciation of materials value' (Camere et al., 2018).

Besides the current bio-based products made from inert materials, living organisms are getting involved in more and more biofabrication concepts. Hence, another sensorial value in the possible future is emerging. The experiential value of livingness, emphasised in the design field, is highlighted again in the biofabrication trend. As the biophilic design suggests, the elements of nature or natural patterns can bring the connectivity with nature to life. Therefore, connectivity with nature is a design focus in biofabrication that incorporates living elements. Besides the natural affinity and aesthetic experience, designers are also trying to bring more alive-like expressions to the biofabricated materials by mimicking the structures and behaviours of organisms. By integrating other sensorial components, dynamic, kinetic, and responsive features are gradually implemented in physical and digital biofabrication and bring new definitions and meanings of materials to people (Karana et al., 2020).

DISCUSSION and CONCLUSION

This literature review has shown six main aspects that constitute biofabrication in the design and innovation field. With two research questions in mind, *material origins, fabrication ways,* and *design considerations* were described to answer the practical factors that designers need to consider. Next, *ecological and biological values, ethos and social values,* and *experiential and sensorial values* were categorised to respond to the values that 'bio' elements bring to the new paradigm of fabrication. In the process, three aspects of values were found to correspond to three practical factors, respectively.

It is worth noting that the boundary between biofabrication and biodesign is blurry in some parts, which was gradually discovered in the reviewing process. This is because that design and innovation projects usually pioneer possible applications. Also, subtopics in a field will merge in different contexts. Moreover, the lexicon for an emerging field often needs to be clarified and still needs to be defined (D'Olive & Karana, 2021; Akyurek et al., 2020).

One of the findings in the reviewing process is that the role and capability of designers to deal with multidisciplinary integration are crucial for the development of biofabrication. As scientific knowledge and biological variables are relatively unfamiliar to most designers, their design sensibilities are somehow confined, and the meaning of involving designers in development will be lost. Designers share similar qualities as scientists in that they also own the spirit of fine-tuning and reflecting on the process. Therefore, several studies proposed that a new interdisciplinary methodology needs to be created to support biofabrication for design practice (Camocini & Vergani, 2021; Camere et al., 2018; Karana et al., 2018).

To conclude, whilst scientists are putting efforts into improving the properties of biomaterials and the biofabrication process, designers and innovators are encouraged to equip themselves to integrate practical factors with abstract values. Thus, meaningful revolution by biofabrication can then realise.

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