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Microbiology meets the fashion world: a paradigm shift in design education and practice through biotechnology

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Abstract

Fashion industry is the second most polluting industry in the world representing a 2 trillion dollars and growing valuation (Pal, 2017). This dual context makes its challenges hard to address. From one side, fashion design education and practice systems have been perpetuating an industrial-focused approach which relies mostly in the economic improvement through fast cycles of product development (Pal, 2017). On the other side, fashion industry has also been closed to either multidisciplinary and transdisciplinary initiatives outside the scope of the artistic disciplines. Therefore, innovative approaches are needed to solve fashion industrial challenges. One of the most promising fields to tackle fashion current environment and technological problems is microbiology (Mazzoto *et al.*, 2021). During the past 50 years, microbiology has played a vital role in solving human grand challenges in health, agriculture, food, and waste management sectors, and it also represents an opportunity for fashion industry as well. Microbiology biotechnological potential for the fashion industry relies mostly on the improvement of toxic waste bioremediation and the development of novel biomaterials and biomolecules. Moreover, the emergent field of synthetic biology is expanding the tools and approaches available, and they can already be seen in the development of engineered living materials that have functional properties (Mazzoto *et al.*, 2021). Despite the urgent need for change, there is still a long way until a more sustainable fashion industry is achieved. Therefore, microbiological research and innovation need maturation to be able to scale-up and reach a global impact for tackling fashion industrial problems.

Key-words

Microbiology, fashion, design, education, biotechnology

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Introduction

Modern fashion practices led to faster production and consumption cycles, which encompasses a greater waste generation (Pensupa *et al.*, 2017). Two of the most abundant wastes generated by the fashion industry are fiber waste and wastewater. For instance, in 2015 alone, around 53 million tons of fiber were manufactured, however, 12% were lost during production processes, and 2% were lost during collection and processing. Around 73% was landfilled or incinerated, and only 12% was recycled (Mazzoto *et al.*, 2021). Therefore, it is estimated that underutilization and poor recycling practices represent more than 500 million euros in losses (Morlet *et al.*, 2017). Another environmental problem of the fashion industry is the extensive use of water and chemicals during manufacture. For manufacturing 1 kg of garment, it is necessary between 1.5 and 6.9 kg of chemicals (Roos, 2017) and around 700 liters of water (Pensupa *et al.*, 2017). The wastewater coming from the use of water to rinse and wash fabrics and garments during the manufacturing process is polluted and significantly toxic, possessing acids, alkalis, detergents, grease, oils, sulfates, solvents, heavy metals, other inorganic salts, fibers and surplus dyes (Madhu and Chakraborty, 2017). Additionally, fast fashion has accelerated the problem by increasing the production cycles. This creates a disposal culture, and the inevitably grow of a second-hand market in developing countries (Manieson and Ferrero-Regis, 2022). Therefore, the dual context between the Global North and the Global South has accentuated. Global South has become the endpoint of tons of discarded clothes, as exemplified by the Kantamanto second-hand market in Accra, Ghana, and a modern route of a colonialist relationship between the richer countries and the is perpetuated (Manieson and Ferreri-Regis, 2022).

The current challenges for designers are systemic since the boundaries between objects, structures, systems, and processes are less defined and much more continuous and evolving (Meyer and Norman, 2020). Everywhere it is found global social, economic, and industrial frames that tailor design briefings. Due to the lack of standard frameworks and methodologies, some designers may professionally grow through experience and rely on learning by accident methods (Meyer and Norman, 2020). Concomitantly, the idea of shareholders is expanding, and they now must incorporate the mid- and long-term impact of projects, products, and services (Meyer and Norman, 2020). It may seem obvious, but the speed of change unveils a challenging question for the current design paradigm, which is the inability of approaches developed in the 20th century to solve 21th century challenges. This results into the hurdle of constantly defining content and methodologies for every project (Whitney and Nogueira, 2020). The hurdles are seen in design practice but also in design educational institutes and the crisis constitutes a problem of context and vision for the design field itself.

One of the most promising fields to tackle fashion current environmental and technological problems is microbiology (Mazzoto *et al.*, 2021). Sustainability is a global trend and every brand and textile manufacturer want to participate (Ertekin *et al.*, 2020). Therefore, these industrial players are interested in introducing more sustainable materials and practices (Francesco *et al.*, 2010). Microbiologists have been researching towards a new approach to harness microbes to this end as well (Mazzoto *et al.*, 2021). Current advances in the biotechnology field pushes forward the comprehension and engineering/fabrication of the coordinated supramolecular and cellular processes of microorganisms resulting in improved structures and functionalities (Hill *et al.*, 2022). As exemplified by biofabrication approaches, which constitutes the automated bottom-up approach that generates biologically functional products through bioprinting or bioassembly (Groll *et al.*, 2016)., microbiology has the potential to add a whole new range of

knowledge and practices to improve the designers' arsenal and the industrial intellectual property portfolio.

The design and fashion challenges

A new educational approach for design

The deep changes made during industrial revolution in the education system hit design education as well, which was repurposed from the interface practice in the arts, crafts, and architecture, to a more focused production for mass markets (Schwartz, 1996). Specifically in the design education case, the goal was to improve the inner country competitiveness in global markets which justified the creation of a partnership between manufacturers and designers (Weisberg, 1989). In the 90's, the Bauhaus classes upgraded and widen the discussion held in the Werkbund. The focus was not the industrial challenges anymore, and it shifted towards the goal of shaping a modern and enlightened culture and society (Droste, 2002). Notwithstanding, a novel transformation in design is necessary, one that encompasses a refocus of the design practice, that merges the individual, industrial, and governmental behaviours that allow a healthier planet, safe from disastrous human activities that could potentially eliminate the risk of a global emergency.

As László Moholy-Nagy did in Chicago in 1937, design must push forward its links with other fields and not only work side by side with industrialists (Malherek, 2018). Once failed, the interest for the cooperative effort of social and natural sciences must be tried once again (Findeli, 1990), for a truly and comprehensive societal transformation (Whitney and Nogueira, 2020). Therefore, the recommendation for design students must be to search how things ought to be and not be conformed to how things currently are (Simon, 1969). This dissatisfied attitude will drive students for an improved learning experience guided by knowledge, practice, and freedom. However, the current unprecedented higher demand for design courses by Government leaders, large corporations and NGOs may stretch the resources of design schools thus limiting the learning experience it is delivering, reducing the quantity of unique and personal development experiences (Baha *et al.*, 2020). So, a suitable approach in design education must embrace a deep awareness for a competency-based model that paints a picture for the student rather than starting from the 'blank' (Baha *et al.*, 2020). It is imperative that a student becomes aware of the self-reflection of what it is mean to be a good designer, the type of designer she or he ought to be, and even if oneself sees her or himself as a designer (Baha *et al.*, 2020). Nowadays, it is common that design students do not fully comprehend the scope of their choice in design disciplines (Julier and Kimbell, 2019). This handicap in their development can be carried over their professional practice causing a numbness in the purpose of designers' careers, making them work towards no "life project" (Manzini, 2015, Escobar, 2018). Thus, design education needs rethinking for instance through improved design educational spaces that could drive and stimulate processes for an enriched design culture (Baha *et al.*, 2020). One last challenge remains coupled to design schools themselves. Design schools must overcome their dominant view for design which executes curricula oversaturated with those visions (Glasser 2020, Fry 2003, Mewburn, 2010). How design schools develop their identities should also change since the process must not be based on geopolitical preferences or based on the perspectives coming from their national and local leaders' (Ghajargar and Bartzell, 2019). If not diverse and independent, design education will form students with tendencies for those biased and standard practices and strategies, hampering their career development. Whilst seeking confirmation and comfort design students will undermine their full unique potential that must also embrace the school and society expectations within the field (Adams *et al.*, 2011, Gray, 2014, Kosonen, 2018, McDonnel, 2015, Tracey and Hutchinson, 2018, Baha *et al.*, 2020).

A revitalized design practice

We live in the storm of the fourth industrial revolution, and it is disrupting the production, management, and government realities we have known for several decades (Schawb, 2017). Therefore, designers need to be empowered by new competences in the physical, digital, and biological spheres (Wilde, 2020). Additionally, they must get comfortable in negotiating consensus throughout a variety of decision-making players in challenging contexts, and be able to simultaneously work with (Wilde, 2020) and against the *status quo*. At today's perspective, the design practice has lost the critical thinking referential through which designers ask themselves what are the necessary "whys" and "hows" for a good design and for a certain desired effect (Dorst, 2003). The current limited scope of design practice, seen in the absence of designers in the decision-making activities was driven by the last major transformation it felt. From the merge of arts and crafts towards a practice for mass production of desirability, consumption and product development in a capitalist economy of scale, design has lost its natural ability of problem comprehension and tension alleviation. The modern world needs the creativity, flexibility, responsiveness, and speed embedded into design practices, mostly when a behavioural change, either individual or organizational, is within the scope of the target project's objective (Whitney and Nogueira, 2020). Up until now, the evolution of design encompassed the competence of helping organization solving complex problems in the face of uncertainty that arise from cultural, social, and emotional factors (Whitney and Nogueira, 2020). However, this evolution still lacks the proper knowledge and practices' standards that may be gathered and disseminated easily and widely by design practitioners (Whitney and Nogueira, 2020).

One of the problems of the design field is related to its difficulty in changing paradigms. Contrary to science and economics, design knowledge is somehow fragmented and relies mostly in more informal standards and theories (Whitney and Nogueira, 2020). Science is fast in creating and implementing new information to format the old frameworks and methods which are constantly advancing. The idea is thus to mix general fields with sub-fields creating space for emergent discoveries that can challenge the current paradigm. However, in the design field, changes occurring through new knowledge takes more time to be perceived and to be implemented in the design community (Whitney and Nogueira, 2020). Additionally, an advancement within a sub-field does not automatically means the entire design field was improved, which is problematic for a collective modernisation, increasing the chance of appearance of neglected areas within design sub-fields (Talke *et al.*, 2009. De Goey *et al.*, 2019, Gallego *et al.*, 2020). However, these facts did not inhibit the advancement of the design *per se*. The body of knowledge is immense, and it guides design practitioners and students alike. So, there is no single and uniform way of practicing design (Whitney and Nogueira, 2020). Still, the informality nature of the field is creating a gap between the study, research, and industrial design practice. Contrary to science or management areas, there is a lack of standardization in the design field (Whitney and Nogueira, 2020, Meyer and Norman, 2020). According to Whitney and Nogueira (2020), "design continues to produce novel solutions to specific problems but falls short in building knowledge that acts as a context for the various activities we call design". For instance, in the case of prototyping, there is no standard framework for its practice, which implies that design students learn mostly by doing, without explicitly understanding the underlying principles of the activity (Whitney and Nogueira, 2020). Therefore, the inherent informality in design constitutes a major handicap in the field since it creates additional teaching challenges, and also creates barriers for adapting to changing contexts (Dewey, 1985). Also contrary to other disciplines where the focus is dedicated to the understanding and analysis of the target phenomena, design is a discipline focused on synthesis and creation of novel things (Meyer and Norman, 2020). Hence, it is obvious that design teaching and practice must incorporate a wide range of disciplines, mostly outside from the design scope, to be able to better fit into a multisectoral context. Examples of those broad range of fields might be core principles of business, experimental methods and statistics, ethics, and appropriate knowledge about the real world (Meyer and Norman, 2020)

As per the need for a paradigm shift, recently Whitney and Nogueira (2020) developed a conceptual model that works for the standardization of design. The model uses seven frameworks to focus designers and projects (Whitney, 2015). One of the main points of the Whole View Model is that it helps teams in complex projects, aiming the uncover of relevant issues by asking the question: “What do we need to know to make change?” (Whitney and Nogueira, 2020). Thus, Whitney and Nogueira (2020) challenge the current paradigm in design by asking if it shouldn’t be the norm for design practice to take into account simultaneously the wellbeing of society and the prosperity of the natural environment. Moreover, they state three claims that forces the design field to react: 1) “pay our real cost, not steal from the future; 2) designing for people, not markets; and 3) building trust, not information pollution.” (Whitney and Nogueira, 2020).

The conceptual attempts to revolutionize design are not new. During the last 50 years, the interconnection between computation and strategy and design have increased. However, this openness is still scarce to fields outside artistic disciplines, but it is observed a higher interest in other fields such as cognitive science and anthropology (Whitney, 2015). At the design practice level, the shift changed from a predictable global economy to volatile and niched economy of choice. Sustainability trends tend to accentuate that shift. The COVID-19 crisis showed that this inadaptation to reality is not exclusive to the design field, thus felt throughout every aspect of human civilization (Wilde, 2020). However, COVID-19 crisis was an indication of the difficulties that humankind will have in the face of global, impactful, and fast occurring events. Climate change, ecosystems and biodiversity loss, social injustices, war, mass migrations, *etc*, may represent the next global crisis. Yet, design may address these challenges as opportunities to rapid reinvent itself either through improved education and modernized practices that better suit this age (Papanek, 1972). However, the need for change and the inevitability of a paradigm shift in design is a decades old issue, exemplified through the work of Ann Light and her team, Arturo Escobar, Buckminster Fuller, Eli Blevis, Ezio Manzini, Vitor Papanek, among others (Papanek, 1972, Wilde, 2020).

Specifically, design approaches need to step beyond the Human-Centered practices and upgrade towards a better comprehension of today’s world. Formally started in 1989 in the Institute of Design, part of the Illinois Institute of Technology (United States of America), Human-Centered Design pioneered the anthropological and cognitive vision for design practice (Whitney and Nogueira, 2020). This led to the global adoption of Human-Centered Design throughout every school and design offices. However, as the current worldwide challenges are demonstrating, putting humans first might not be a wise choice. Since the *user personas*, *user journeys*, and ethnographical research are widespread terms for designers nowadays, these Human-Centered approaches paved the way for a more comprehensive approach for innovation (Weil and Mayfield, 2020) and design management (Kumar and Whitney, 2007), but left behind the comprehension of the design impact in the other spheres, such as the natural environment. However, the ability to merge distant domains is natural to design. As Staatliche Bauhaus imagined more than 100 years ago, the merging of disciplines remains at the core of the design practice. From the reconciliation between the fine and applied arts, now it is again time to develop a new formal language of design in order to do justice to the global world challenges (Meyer and Norman, 2020). The New European Bauhaus initiative represents a novel approach within this scope (Rosado-Garcia *et al.*, 2021). However, contrary to the Bauhaus School, the main goal is not to improve industrial processes but rather to adapt human civilization to a sustainable and natural world. In accordance to the New European Bauhaus initiative, several authors have been encouraging a paradigm shift in design teaching and practice (Friedman *et al.*, 2014a, Friedman *et al.*, 2014b, Norman and Klemmer, 2014, Batra and Seifert, 2015, Norman, 2016, Norman and Spencer, 2019). Namely, it must be a common imperative the interrelation of people, organizations, and the natural environment, focusing the health, happiness, and prosperity of each of those dimensions (Whitney and Nogueira, 2020). Despite addressed by both social innovation and sustainable design subdomains, the field itself lacks the

capability to implement solutions to global problems at a global level. The truth is that a vast majority of design projects are neither sustainable nor prominently social (Whitney and Nogueira, 2020). One way to improve design practice in the abovementioned route is to add circular economy-based knowledge to it. In a recent study, Sumter and colleagues (2020) identified 7 novel competencies for a more circular design practice: 1) design for multiple use cycles; 2) design for recovery; 3) circular impact assessment; 4) circular business models; 5) circular user engagement; 6) circular economy collaboration; and 7) circular economy communication. In brief, the focus must target the limit of novel production from scratch and to bring a collaborative workplace throughout the value-chain in order to maximize the existing resources' potential (Sumter *et al.*, 2021).

All the above-mentioned points also apply to fashion design teaching and practice. There are both personal, organizational, and other external challenges to build a more sustainable fashion design process (Hur and Cassidy, 2017). These challenges are: lack of consensus and knowledge about sustainable design; insufficient sustainable-based design approaches in fashion; insufficient perception of the benefits and trade-offs in styling, cost structure, trends, *etc*, when implementing such approaches; uncategorized consumer demand; low level of business-related incentives; and lagging behavioural changes and purchasing decisions towards sustainable choices (Hur and Cassidy, 2019). But, the first step for change must be the embrace of conflict and failure as tools to success. Once and for all the tasks that may arise from conflict and failure must be devoided of judgment since they are inevitable in this multisectoral world context (Krippendorff, 1995). The new imperative for design practice must follow the values of integrity, imagination, freedom, cultural plurality, and must promote a conscious behaviour that brings the best in people (Baha *et al.*, 2020). Stakeholders and shareholders must acknowledge that the *status quo* is capping the gains in the future, despite bringing them at the present. They must realize that only through a combined educational and industrial effort, the upcoming challenges may have a chance to be correctly addressed and, perhaps, solved.

The fashion industry challenges

One hundred and fifty billion garments are produced annually and roughly half are discarded within one year of use (Rudenko, 2018). Fashion environmental cost is dramatic (Pal, 2017). The value-chain is composed of several steps that mounts the resources necessary to produce fashion products. In detail, raw materials are extracted, fibers and yarn are produced before fabric is available, then fabrics undergo wet treatments. After ready, fabrics are distributed to garment makers who produce them and distribute to retailers and wholesalers. At the end of the value-chain, the end user terminates the process and the fashion piece, mostly, goes to waste (Kwon *et al.*, 2020). It is not uncommon that clothes are used only during the first year after being bought, then the common route is disposal, which represent a problem worth more than 140 million euros in the UK alone (Moorhouse, 2020). Additionally, the entire supply chain is producing residues, either due to rejection or discard, and it may represent around 15% of total fabric manufactured in factories (Cooper *et al.*, 2022).

One endpoint of the fashion industry's residues is the soil. Soil is one of the most diverse and rich habitats for microorganisms (Adhya and Annapurna, 2018, Biswas and Sarkar, 2018, Dubey *et al.*, 2019). Climate change and human activities such as the use of hazardous agrochemicals, negligent discharge of industrial wastes, maluse of antibiotics, *etc* (Zhang *et al.*, 2016, Ibekwe *et al.*, 2018, Ji *et al.*, 2018, Ou *et al.*, 2019, Zhen *et al.*, 2019, Wang *et al.*, 2020, Anand *et al.*, 2021, Yang *et al.*, 2021, Feng *et al.*, 2022, Wu *et al.*, 2022) are damaging the ecological cycles and degrading the soil regulation which causes the reduction of diversity and the loss of natural resources that could be otherwise exploited (Cavicchioli *et al.*, 2019, Dubey *et al.*, 2019).

The fashion industry wastewaters represent an additional risk for the environment since the presence of colour blocks light penetration thus harming primary producers through photosynthesis rate reduction (Mazzoto *et al.*, 2021). This reduction leads to a decrease rate of dissolved oxygen in the water which is prejudicial to the habitats (Lellis *et al.*, 2019, Lalnunhlimi and Krishnaswamy, 2016). Moreover, many utilized dyes have carcinogenic and toxic properties, and they are persistent in the environment due to their chemical composition, which increase the chance of being ingested throughout the food chain (Lellis *et al.*, 2019, Przystas *et al.*, 2012, Chequer *et al.*, 2013). Dyes generate hazardous waste through persistence in industrial wastewaters, and their decomposition is environmental unsafe (Dave *et al.*, 2015, Usman *et al.*, 2017, Dawkar *et al.*, 2009). The loss of dyes during fashion manufacture's process is paramount, constituting a major problem. Despite not well documented, between 2-50% represent residues, accounting to almost 200,000 tons dumped into effluents each year (Chequer *et al.*, 2013, Madamwar *et al.*, 2019). However, azo dyes are widely used due to their low cost, and the variety and stability of colours available (Mazzoto *et al.*, 2021). Representing around 70% of all dyes produced, they are resistant to microbial degradation (Sarata *et al.*, 2011, Arora, 2014). Right after azo dyes, the second most used category of dyes is anthraquinone, which possess superb performance at a low cost albeit its toxicity to humans (Varjani *et al.*, 2020). Despite being resistant to microbial degradation, azo dyes can be metabolized inside the gastrointestinal tract by the gut microbiota into aromatic amines, which are compounds with carcinogenic properties (Feng *et al.*, 2012). Therefore, new protocols and processes need to be developed in order to eradicate the environmental and potential health problems associated with the use of dyes during the garments manufacturing process (Mazzoto *et al.*, 2021).

The textile composition is dependent on the fiber choice, fiber arrangement, which determines its strength, durability, appearance, and texture (Mazzoto *et al.*, 2021). Fibers can be divided into two groups: man-made and natural fibers. Natural fibers include cellulosic-based materials, such as cotton and linen, and protein-based, such as wool and silk (Mazzoto *et al.*, 2021). Cotton is the most used natural fiber on the market, representing around 35% of all fibers used (Roos, 2017). However, the environmental footprint of carbon is high due to the extensive use of water, pesticides, insecticides, and fertilizers (Mazzoto *et al.*, 2021). However, the majority of fibers on the market is synthetic, being manufactured from monomers sourced from fossil oil feedstocks (Mazzoto *et al.*, 2021). Albeit their variety, the most common ones are polyester, polyamide, elastane, polyacrylic, and aramid (Sinclair, 2015). Unfortunately, the low biodegradability property of synthetic fibers is posing additional questions about its use in fashion industry, where their presence in the deep sea, in the Arctic sea ice, inside fish, and shellfish constitutes crucial evidence of the problem (House of Commons, 2019). Natural fibers also have environmental impacts. As an example, the Aral Sea in Central Asia has been suffering from intensive cotton farming practices and now it is depleted of water and other resources once plenty in the region (Spoor, 1998, Zhang *et al.*, 2019).

The fashion supply-chain is vast, and it is currently impossible to track the detailed environmental impact of its activity. Therefore, it is paramount to gather standard measurements throughout the supply chain and promote its wide documentation. Major suppliers must be aware of the full scope of the harming impacts of their activity. Moreover, they should improve the network of partners to be able to, collaboratively, address the environmental challenges in a robust, honest, and fast way. Ultimately, as seen in other

industries, microbiology is a field that represents a huge potential to guide mitigation and innovation projects for the fashion industry. There are already several projects underway with this mindset, however, the scope has been somehow limited and driven mostly by a marketing ambition. Start-ups together with mature enterprises must combine their efforts to improve the scale of the projects and so increase the speed of change towards an environmental safer industrial practice.

Solution through microbiology

Bioremediation, biomaterials and biomolecules

During the past 50 years, microbiology has played a vital role in solving human grand challenges in fields such as health, agriculture, food security, waste management, among others (Thallinger *et al.*, 2013, Singh *et al.*, 2016, De Giani *et al.*, 2021, Fu *et al.*, 2021, Gilmour *et al.*, 2021, Iyer *et al.*, 2021, Kaur *et al.*, 2021, Soh *et al.*, 2021, Liu *et al.*, 2022, Montano Lopez *et al.*, 2022). The economic benefit of inhabiting a microbial world is manifold and accounts for billions of euros annually (Anand *et al.*, 2021). The ecosystem services microbes provide to humanity and nature as a whole are related to the economic and ecological sustainability, adaptation and mitigation of climate change, biotechnology and agricultural applications, and biogeochemical cycles (Rousk and Bengston, 2014, Zhu *et al.*, 2017, Martines-Espinosa, 2020, Bakker and Berendsen, 2022).

The advancement of novel and upgraded techniques for isolation and characterization of microorganisms have increased their study as a tool for biotechnological research, development, and innovation (Anand *et al.*, 2021). Microbial Culture Collections represent a resource where microorganisms can be investigated for potentially applications (Guidice and Rizzo, 2020). Started one century ago, these collections, under management of the Biological Resource Centre's (BRC), have the goal to collect, preserve, distribute, and to disseminate relevant information of microbial strains (Anand *et al.*, 2021). The work of the BRCs relate to the conservation, quality control and curation; identification, and authentication, and taxonomical classification; data gathering, management, and sharing of microorganisms-related information and good practices. Microorganisms, DNA, genomes, plasmids, and viable but not yet culturable microorganisms can be sourced in biological or environmental matrices (Smith *et al.*, 2014, Diaz *et al.*, 2021). The Organization for Economic Cooperation and Development have been supporting the improvement, utilization, and maintenance of these collections (Smith *et al.*, 2014). The main purpose of these microbial culture collections is twofold. Firstly, it guides the conservation of natural and built habitats through isolation and conservation of microbial diversity. Secondly, it facilitates the research and development of such microorganisms by the wider public through generation of biotechnological strategies (Diaz *et al.*, 2021). One of the pitfalls of their work is the focus on reference strains, thus limiting the work on the phenotypical variation of other potentially interesting strains. Another handicap of BRC's is the need for an improved capacity to account for a less fragmented activity and better-quality materials and support, allowing both academic and industry researchers access to the required strains (Anand *et al.*, 2021). Microbial collections will need more funding in order to hire experts in taxonomy science, upgrade their infrastructure to work with modern technologies such as next-generation sequencing, and to increase their communication strategies to a wider public, improving their recognition, specifically in terms of their capability to tackle biodiversity challenges (Anand *et*

al., 2021). One example is the production of novel biopigments and biocolorants. The non-carcinogenic and non-toxic potential nature represent advantages of biopigments and biocolorants (Malik *et al.*, 2012). This trend is gaining traction also due to the biodegradability of these natural compounds.

Currently, several approaches of using biological processes, based on microbial degradation of the pollutants and toxic compounds present in fashion industrial wastewater are being attempted and they have been fully reviewed elsewhere (Romore *et al.*, 2006, Singh *et al.*, 2015, Mazzoto *et al.*, 2021). Microbial biomass and microbial fibers, biosurfactants, and biocatalysts can be explored instead of other less sustainable products (and practices), such as pesticides, solvents, monomers, *etc* (Mazzoto *et al.*, 2021). Additionally, biobleach, microbial dyes, and microbial-based degradation processes, like waste remediation, recovery, and transformation can also be investigated and developed according to the industrial needs (Mazzoto *et al.*, 2021). The current industrial practices of textile recycling involve the second-hand markets and reprocessing rags, which corresponds to low added value (Hu *et al.*, 2018). From the dumped fibers, only natural fibers have potential for further microbial exploration, for instance by microbial use as carbon source, thereafter, producing ethanol, organic acids, enzymes, and polysaccharides (Mazzoto *et al.*, 2021). However, efforts have been recently made to develop microbial-based solutions to waste generated by the use of synthetic fibers (Mishra *et al.*, 2020, Mishra *et al.*, 2022).

Besides natural products produced by microbes found in the wild, there is also other approaches under investigation. One of those approaches is to increase the performance of textiles through incorporation of living microbes that can functionalize the garment. In 2015, Yao and colleagues (2015) developed a material that responded to body moisture using the absorbent properties of *Bacillus subtilis natto*. In the same context, the skin microbiome is being widely studied in a project that has gained media attention under the name of "Dr Armpit" (<https://drarmpit.com>). Broadhead and colleagues (2021) recently studied the impact of living microbes in the future of clothing. In their view the fashion industry must pay attention to the skin microbiome and improve the care related to the antimicrobial finishing of garments, alongside with the potential of functionalizing garments with living microbes that can diminish malodour and eventual skin infections (Broadhead *et al.*, 2021). Therefore, a new subcategory of products is emerging, the skin probiotics (Knackstedt *et al.*, 2020). Another example is the engineering of microbes to produce spider silk (Fahnerstock and Bedzyk 2000, Foong *et al.*, 2020). Spider silk light, strength, and resistant properties make it a good material for clothing (Mazzoto *et al.*, 2021). Although, the limitation is its challenging industrial production and thus the ability to engineer microbes in order to surpass that handicap may represent an opportunity for designers and microbiologists alike (Scheibel, 2004, Bai *et al.*, 2015, Foong *et al.*, 2020, Zhu *et al.*, 2020).

In terms of biomaterials, bacterial cellulose has been recently studied (Chiesa *et al.*, 2018, Mazzoto *et al.*, 2021, Wang *et al.*, 2021). Cellulose is the most abundant material on the planet and bacteria can produce it with diverse properties, like morphology and structure, make it applicable to different uses (Wang *et al.*, 2021). Bacterial cellulose is constituted of an unbranched polymer of β -1,4-linked glucopyranosyl residues (Cacicedo *et al.*, 2016) resembling plant cellulose and it is easily isolated as a fiber (Mazzoto *et al.*, 2021). Bacterial cellulose is formed by the assemblage of microfibrils into nanofibrils which in turn are assembled into microfibrils (Cacicedo *et al.*, 2016). The absence of lignin, hemicellulose, and pectin represents an advantage of bacterial cellulose when compared with plant cellulose (Mazzoto *et al.*, 2021).

Several bacteria are cellulose producers, and the members of the recently reclassified genus *Komagateibacter* are the most well studied (Mazzoto *et al.*, 2021). Recently, media attention was given to kombucha, a slightly fermented drink with oriental origins (<https://www.nytimes.com/2019/10/16/style/self-care/kombucha-benefits.html>). Kombucha is produced through the infusion of black and or green tea to a sugary broth (e.g., 5%-8% v/v sucrose) inoculated with yeasts and bacteria (known as “scooby” – symbiotic community of bacteria and yeasts) (Dima *et al.*, 2017). During the fermentation process, bacteria present in the mixture tend to produce cellulose at the surface-liquid layer which thickens with time. Amongst the fashion designers exploring bacterial cellulose, Suzanne Lee from BioCouture is producing it as a textile material, however, bacterial cellulose may also be developed as fibers and yarns, therefore expanding its application (Chiesa *et al.*, 2018). Bacterial cellulose produced using methods inspired by kombucha fermentation constitutes a biofilm or a mat that can be removed from the liquor, rinsed, dried, and potentially tailored to obtain other features such as impermeability (Fernandes *et al.*, 2019). This product can perform as a textile and works with aesthetics and properties similar to animal leather (Wood, 2019). Despite being termed a “vegetable leather”, bacterial cellulose micro and nanostructure is different and resemble a nonwoven fabric (Wood, 2019). However, research is underway to test techniques of garment construction such as stitching, bonding, and three-dimensional shaping (Kaminski *et al.*, 2020, Costa *et al.*, 2021, Bolzan *et al.*, 2022), and despite its extensive research, intrinsic limitations may hinder its wide use at scale. For instance, bacterial cellulose is a naturally hydrophilic material and thus cannot be worn during raining and under high humidity levels, neither it withstands washing without degrading (Wood, 2019). Our skin can also get wet occasionally and this fact can limit the application of bacterial cellulose *per se* as a textile material (Wood, 2019). Besides bacterial cellulose, mycelium-based composites haven also been studied for potential use as fibers (Mazzoto *et al.*, 2021). Growing in an aqueous substrate, a complex network of fungal hyphae is formed and its intertwined network of fibers can be recovered, deactivated, and dried for further use (Camere and Karana, 2018). The low cost and easy laboratory feasibility of mycelium makes it attractive for manufacturers (Mazzoto *et al.*, 2021). The mycelium structure and mechanical strength comes from its composition of chitin, glucans, and glycoproteins (Haneef *et al.*, 2017). Two of the fungi that can be investigated to mycelium production are *Ganoderma lucidum* and *Pleurotus ostreatus* (Haneef *et al.*, 2017). One of the first scientists to research onto mycelium and its fiber application in clothing was Aniela Hoitink (Nai and Meyer, 2016). She developed a composite product made by *Schizophyllum mycelium* called MycoTEX by Neffa (Nayak *et al.*, 2020). Other initiatives and projects are Mylo from Bolt Threads, MycoFlez from Ecovative, Reishi Fine Mycelium from MycoWorks, among others (Mazzoto *et al.*, 2021). These initiatives have been gathering media attention and collaborations with major brands like Adidas (<https://www.forbes.com/sites/timnewcomb/2021/04/22/creating-adidas-mushroom-based-stan-smith-mylo-sneakers/?sh=7c632b527c0d>). The manufacturing process of mycelium represents several advantages comparing with cotton, such as fast production and the elimination of the sipping, weaving, cutting, and sewing steps. Moreover, it uses less water, less intermediary chemical products, and therefore, it produces less waste (Nai and Meyer, 2016, Camere and Karana, 2018). However, challenges remain for the widescale industrial production that could account for the replacement, for instance, of animal leather in fashion manufacturing.

Synthetic biology

Apart from natural biomaterials, engineered living materials constitutes another frame of opportunity. Once stated as science fiction, these applications might convert into reality since synthetic biology field could develop standardized frameworks to allow the edition of desired properties and functions within complex cellular matrices (Gallup *et al.*, 2020). As plants possess genomes that allow them to programme the precise growth and differentiation in an array of tissues such soft flowers, petals, nut shells, the same can be achieved for biotechnological purposes as well. In practical terms, the biotechnological revolution of synthetic biology represents an opportunity to surpass the limitations seen in the microbial growth and target-compound production. Temperature, pH, dissolved oxygen, available nutrients, dissolved organic matter, metals, among others impose stress to the microorganisms which may handicap their biotechnological potential (Mazzoto *et al.*, 2021). Therefore, tailoring microbes to surpass those limitations and improve their resistance to stressors and increase the production yields constitute a via towards novel microbiology-led innovations. The potential of synthetic biology can be addressed by the manipulation of community communication networks, extensive and precise regulation of gene expression, and engineering of syntrophic interactions (McCarty and Ledesma-Amaro, 2019). The predictive understanding of synthetic biology is expanding the applications in several fields, since the computational models are increasing the efficacy of biotechnological developments (Carbonelli *et al.*, 2019, Radivojevic *et al.*, 2020, Gallup *et al.*, 2021, Leggieri *et al.*, 2021). Recently, Radivojevic (2020) developed an automated recommendation tool that performs machine learning and predictive modelling techniques to inform synthetic biology approaches without the need of a comprehensive understanding of the biological system. As people do not need to understand how to build a vehicle to drive it, the same might be a reality for the synthetic biology field soon.

Rather using single microorganisms, scientists are now engineering whole communities for biotechnological purposes (McCarty and Ledesma-Amaro, 2019). The progress in synthetic biology has paved the way for construction microbial consortia aimed at tailored behaviours like bioproduction of drugs, biofuels, biomaterials in defined environments. The advantages of working with microbial consortia are the division of labour between the community members, spatial organization, and resilience to a myriad of stressors (Bassler and Losick, 2006, Stenuit and Agathos, 2015, Tsoi *et al.*, 2018, McCarty and Ledesma-Amaro, 2019). Still, the engineering scope of dynamic communities presents a new range of challenges and successful applications are scarce (Zenlges and Palsson, 2012, Johns *et al.*, 2016, Faust, 2019). The biological chassis is more complex when millions of microorganisms are intended to work towards a single objective. Noack and Baumgart (2019) recently studied the impact of genome reductions on the performance of biotechnological relevant microorganisms. They developed the concept of Community of Niche-optimized Strains that indicates that the energy conserved by deletion of expressed genes lead to a simplified strain that gained fitness performance only inside its community. This means that the environment guides the genome reduction by the proper community management of the common goods (Noack and Baumgart, 2019). Therefore, the Black Queen Hypothesis may be revisited in order to expand the toolset of synthetic biology for the improved utilization of microbial consortia in biotechnological applications (Liu and Xu, 2022). The Black Queen Hypothesis theory assumes that biological systems evolve to simplify (Morris *et al.*, 2012, Liu and Xu, 2022). In practice, this means that some community members make a selfish, or cheater, use of the common goods by taking advantage of cooperation (van

Tatenhove-Pel *et al.*, 2021). The free use of metabolites produced by others (bacteria, or other organisms) originates the loss of those metabolic functions and genes in the taker, representing a coevolution scenario (Morris *et al.*, 2012). The comprehension of the interplay between parasitic, symbiotic, and mutualistic interactions within a single community can increase the arsenal of approaches that synthetic biology can use to develop microbial consortia with efficient cost and yields (Zomorodi and Segre, 2016).

Consequently, synthetic biology represents the next opportunity for the industrial revolution. Its potential can be summarized by a full-range of automation-fuelled industrialization, improved DNA design, creation of synthetic genomes and artificial cells, experimenting with data from whole-cell simulations, all around biosensing capacity, real-time tailored evolution, harness of whole communities and multicellularity, and materials with enhanced DNA-encoded properties (Gallup *et al.*, 2021). Since we live in a climate emergency era (McHugh *et al.*, 2021), all these features can be used for engineering microorganisms and entire microbial communities to reach sustainable goals. For the fashion industry for instance, the production of bacterial cellulose, spider-microbial silk, and mushroom mats are being increasingly explored. However, industrial applications are still in its infancy and further research and pilot projects are needed before a full industrialization can be achieved (Gandia *et al.*, 2021, D'Itria and Colombi, 2022, Ramezaniaghdam *et al.*, 2022).

Challenges/ opportunities

Despite recent research and development advances, there are still industrial, performance, and market challenges regarding the potential of microbiology to be explored in major fashion industry's issues. These challenges are related to the uniqueness and innovative nature of the newly generated products (Mazzoto *et al.*, 2021). The need of research and development is paramount to improve the new biomaterials' and microbial processes' comprehension, making them easier for scaling up and to develop more competitive products (and microbial services) in terms of quality and performance. Still, the promise of microbiology as a tool for fashion industry improvement is clear but perhaps far. Nonetheless, it would benefit from the discovery of better fitted microorganisms, enzymes, biopolymers, molecules, and better-quality industrial processes and bioreactors (Mazzoto *et al.*, 2021). Genetic engineering of microbes through systems and synthetic biology holds a relevant future for the field as well (Yu *et al.*, 2009, McCarty and Ledesma-Amaro, 2019). Additionally, through the increase of society awareness towards sustainability, the need of more sustainable products and services, and new legislation pushing forward environmentally focused laws, fashion industry is feeling the pressure of a paradigm shift. Besides the microbes tanned in the wild and studied towards industrial applications, a renewed attention must be made into the microbial culture collections (Anand *et al.*, 2021). Curated by the BRCs, these collections harbour a truly gold mine for biotechnology. In summary, the true revolution is to see biology as a manufacturing discipline: cells as miniaturised factories with the potential to be deployed anywhere at scale with no extra costs to upgrade (Gallup *et al.*, 2020). This is far from what has been observed so far with bio-based materials' substitutes for a predominantly linear manufacturing industrial value-chain. However, designers must embrace the biological disciplines in general, specifically microbiology and biotechnology interpreted as a manufacturing discipline, and include their processes into consideration throughout design education and practice. So, a shift in design practice will

encourage a new wave of design education and *vice versa*, constituting a proliferation of an improved body of knowledge and practical frameworks to tackle the most urgent planetary challenges.

Conclusion

Design teaching and practicing need a paradigm shift and it will constitute the normal evolution of the design field. This evolution will gain impetus from the historical Bauhaus School and the new European approaches such as the New European Bauhaus. The realistic movement of the design from its tendency to be informal and the synthesis basis of its practice will dramatically change to better accommodate information and methods from other fields such as natural and behavioural sciences. Therefore, a wider view of design is mandatory. As seen in the recent biotechnological endeavours to tackle fashion industrial challenges, microbiology represents an escape route from the current crisis. Innovative and circular-based projects are aiming to close the resources' gap, with the long-term goal of eliminating the need of virgin materials.

Currently, there may be enough technologies and innovations to solve fashion industry's main problems. However, there is a long way until sustainability be achieved. Fashion industry value-chain is complex, and it will take global cooperation to reinvent it. Ultimately, fashion and other industries must cope with the natural system and not the other way around. Innovation must stay in focus because punctual and small initiatives cannot hold the solution by themselves. If they are only and foremost communicated throughout the value-chain and to the end users, they must be interpreted as greenwashing.

Additionally, an improved applied research and development of microbial culture collections, the extensive use of biomaterials and biomolecules, and bioremediation solutions are necessary to improve the resilience of the current fashion industry models. However, these approaches might not be sufficient to foster an ethical and sustainable change. The promise of synthetic biology to engineer functional and living materials are routes that both designers, scientists, stakeholders, and governmental entities must embrace to speed up the pace for a paradigm shift in design practice, which will acknowledge an update in design education as well.

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