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RESEARCH ARTICLE



Materials biography as a tool for designers' exploration of bio-based and bio-fabricated materials for the sustainable fashion industry

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ABSTRACT

The fashion industry is highly responsible for critical environmental problems and the sector is increasingly aware of the urgent need to embark on a sustainable transition. Materials, primarily textiles, are particularly problematic for the sector's unsustainability, despite the intensive research into alternative solutions that is currently underway. This article presents a comprehensive analysis of these socio-environmental challenges and describes how governments, industry, and designers are seeking to address the situation. Furthermore, it identifies a panorama of alternative bio-based and bio-fabricated materials that could facilitate the transition toward more sustainable fashion. We present a selection of 24 case studies of newly developed bio-based and bio-fabricated materials and group them by their origin. Analysis of the cases led to the delineation of five "materials biography categories" to help understand the prominent narratives and to communicate their characteristics and fundamental attributes. This taxonomy also serves to support concepts for a circular economy by helping to build a sort of "material passport" or "product biography," two concepts underpinning the outcome of this study, and emphasizes the need for tools to further the communication and traceability of these emergent materials. We propose "materials biography," an overarching idea that catalogues essential dimensions and offer it to designers, companies, and final users to enhance their perception and awareness of such novel materials.

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Introduction

The fashion industry, like other production sectors, has adopted the paradigm of continuous growth without considering the finiteness of resources, the complexity of human productions, and the related array of environmental issues. At the same time, firms in this industry seem at present to be most in turmoil around a purported transition toward sustainability, with public opinion focused on the mismanagement of environmental and social issues linked to fashion production (Gazzola et al. 2020).¹ As affirmed by the president of the United Nations Economic and Social Council (ECOSOC) at the Sustainable Fashion Summit in 2019, "sustainable fashion is key to the achievement of the 2030 Agenda."² Fashion is a US\$2.5 trillion dollar industry that employs approximately 60 million people worldwide, most of them women. Undoubtedly, fashion has a pronounced impact on the economy and the global environment (Brydges 2021). The model of consumption that characterizes our throwaway society has been vigorously advancing in the fashion sector, culminating in the

propagation of "fast fashion," the demand for disposable clothing at low prices (Jacometti 2019). Numerous studies (Niinimäki et al. 2020; Niinimäki 2018; Sandin et al. 2019) have described the considerable environmental and social costs and other negative impacts of the fast fashion phenomenon including the mistreatment of animals and the exploitation of people through poor working conditions (Moretto et al. 2018; Provin et al. 2021).

Considering garments as disposable goods implies excessive consumption of resources while disregarding the long and complex supply chains that characterize the textile and fashion industry (Moretto et al. 2018). Indeed, each production stage has an environmental impact due to water, materials, chemicals, and energy consumption. Although these impacts mostly occur in countries that manufacture textiles and apparel, waste is everywhere. Brands now produce nearly twice the amount of clothing they did before 2000. Current fashion-consumption practices result in large amounts of textile byproducts being incinerated, landfilled, or exported to developing countries. Only 1% of prematurely discarded

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clothing is recycled, primarily due to the widespread lack of adequate technology (Jacometti 2019).

For all of these reasons, there is a need to develop new materials and to rethink existing ones without foregoing their expressive, sensorial, and experiential dimensions (Neto et al. 2019; Provin et al. 2021). Materials have long provided cultural and innovative content for all the creative fields, including fashion design (Ricchetti 2017; Salolainen, Leppisaari, and Niinimäk 2018). The fashion expert Ayesha Ahmad (2020) stated, “The future of [the] sustainable fashion industry requires going back to nature and connecting with it on a deeper level.” The bio-based and bio-fabricated materials which form the subject of this study (explained in detail below) present alternatives that could transform fashion into a more sustainable industry. The economic and social benefits of bio-fabrication are evident and have already been extensively highlighted in the literature with respect to their ability to improve healthcare and biomedical products (Otto et al. 2016; Mironov et al. 2009). The uptake of new material development by society through tangible applications is a crucial undertaking, and, in the case of bio-fabrication, this is still an ongoing process. The latter accounts for the lack of specific literature on the social benefits that bio-fabrication can bring to design in general and fashion materials in particular. Notwithstanding, there are already specific projects initiated precisely to improve the social aspects of fashion through materials and production processes (Drazin 2015; Rognoli et al. 2017). Accordingly, it is plausible to imagine how, in the near future, the application of bio-fabrication to materials might contribute positively to the social and economic sustainability of the industry.

Achieving more sustainable fashion requires action on its complex and geographically expansive supply chain, of which the materials and processing technologies are key considerations. Researchers focused on sustainability and new possibilities for textile materials have recently identified upcycling, smart textiles, living organisms, and bio-based materials as possible new directions for sustainable fashion (Provin et al. 2021). These alternatives make sense because the use of resources from circular and/or bio-based origins can extend product-life cycles and establish diverse emotional bonds with future users. Initial research shows that the experiential qualities of bio-based and bio-fabricated materials can offer esthetic value by promoting new experiences and empathy for the natural environment (Sayuti, and Ahmed-Kristensen 2020).

This article discusses emergent material alternatives that could help catalyze the transition toward more sustainable fashion. The general objective is to

highlight how emergent approaches to textile design, as suggested by the “materials experience” concept (Karana, Pedgley, and Rognoli 2014) and DIY (Do It Yourself) Materials (Rognoli et al. 2015; Rognoli and Ayala-Garcia 2021), positively contribute to the proliferation of alternative and sustainable materials for fashion. The study evaluates the different materials solutions, focusing on bio-based and bio-fabricated materials. Further, we identify and explore 24 case studies, investigating fundamental traits by framing a taxonomy of biographical categories for some of the bio-fabricated and biomaterials already on the market. Analysis of these cases gave rise to the delineation of five “materials biography categories” that enable an understanding of prominent narratives by portraying their properties and characteristics, particularly those relevant to the materials experience. These categories can also contribute to the circular economy in building types of “material passports” or “product biographies.” The latter two foundational concepts, in combination with the outcomes of this study, demonstrate the need for tools that enable communication and traceability of emergent materials. We propose “materials biography” as an overarching concept that encompasses all categories that offer significant potential for exploration by designers, companies, and users to enhance their perception and awareness of these novel materials.

The remainder of this article is organized as follows. First, we provide an account of the socio-environmental problems linked to the fashion industry. The next section describes our cases of bio-based and bio-fabricated materials and outlines the “materials biography categories.” We then present and discuss our findings and, finally, conclude by providing a summary and suggestions for further research.

Socio-environmental problems linked to the fashion industry

Global awareness of the social and environmental impacts of the fashion industry is becoming more tangible and evident. Accompanying the exponential growth in output during the early 21st century have been major issues connected to materials with special concern focused on outsourcing and end-of-life management. The following discussion considers these issues in detail.

Materials

As one of the most important production sectors worldwide today, the textile sector is notable for its extraordinary amounts of waste and pollution derived from the fact that industrial operations are still characterized by a linear economy, with less than 1% of the material used to produce clothing

recycled into new garments (EMF 2017). Since 1975, the volume of textiles has almost tripled and the total production of synthetic fibers has expanded by 60% (EEA 2021). In the last decade, the price of clothing decreased drastically along with the length of its use life, leading to the “fast fashion” phenomenon (Niinimäki et al. 2020). This situation would not have been possible without the expanding use of polyester which is a relatively inexpensive and readily available raw material. In 2016, about 21.3 million tons of polyester were used in clothing, an increase of 157% from the about 8.3 million tonnes used in 2000 (Cobbing and Vicaire 2016). Synthetic fibers such as polyester increase the overall environmental impacts of textile production in terms of carbon-dioxide (CO₂) emissions and energy consumption (Zhao et al. 2021) to the point where apparel consumption represents the fourth most greenhouse-gas (GHG) intensive lifestyle domain in Europe (Vladimirova 2021). Moreover, with every laundering cycle, microfibers of this non-biodegradable plastic are released into the environment, evading wastewater-treatment plants, ending up in rivers and seas, and adversely affecting aquatic ecosystems (EEA 2021).³ Once present in ecosystems, microfibers can host invasive bacteria and be ingested by marine animals and thus lead to potentially harmful impacts on both aquatic life and humans.

Bio-based renewable materials have a long tradition in fashion history, but since the widespread industrialization and globalization of the sector even materials of natural origin are no guarantee of sustainability. Bio-based fibers can lead to reduced GHG emissions, but their production still requires a significant amount of water and land (Zhao et al. 2021). For instance, cotton, one of the most widely cultivated natural materials for apparel production, requires large amounts of water (2,700 liters of fresh water for a single cotton T-shirt). According to the United Nations Conference on Trade and Development (UNCTAD), some 93 billion cubic meters of water are used by the fashion industry annually.⁴ Moreover, textile processes have been estimated to be the second largest polluter of clean water globally (only agriculture is larger) (Kant 2012) and responsible for 20% of all contamination due to dyeing and treating fabrics with toxic chemicals and applying pesticides to grow raw materials.⁵

Outsourcing

The contemporary textile industry for fashion is highly globalized (Crewe 2017) and most of the pressures and impacts related to consumption of clothing, footwear, and household textiles in Europe occur in other regions of the world where the

majority of production takes place; this is the case for 85% of primary raw materials use, 92% of water use, 93% of land use, and 76% of GHG emissions (EEA 2021). Outsourcing to developing countries is a way to relocate impacts and is also associated with increased negative effects from outdated production facilities and coal-dominated electricity-generation infrastructures. The latter increases the environmental footprint of textile products, especially in countries that produce large amounts of polyester such as China, Taiwan, Korea, Japan, and Indonesia (Karthik, and Murugan 2017; Zhao et al. 2021; Aizenshtein 2017). Outsourced production, a common business practice for European and North American brands, also hides low labor costs and avoids adherence to strict regulations related to the safety of production, both for the environment and for workers. In recent years, the media have highlighted social and environmental issues and contributed to increasing consumer demand for ethical and sustainable manufacturing solutions (Cerchia and Piccolo 2019). Responses from companies and governments are slowly becoming manifest.

The Accord on Fire and Building Safety in Bangladesh (generally referred to as the “Accord”) is an independent, legally binding agreement between brands and trade unions to work toward a safe and healthy garment and textile industry in this South Asian country. It is intended to enable a working environment where no worker needs to fear accidents that could be prevented through appropriate health and safety measures.⁶ However, poor working conditions in developing countries are a fundamental feature of the low-cost clothing that drives the business model for fast fashion. Child and forced labor are deployed to produce cotton in at least 18 countries (Riordan 2020) and workers are routinely exposed to harmful chemicals used in the washing, dyeing, and finishing of fabrics. Approximately 3,500 substances are used in textile production and 750 of them have been classified as dangerous for human health and 440 as hazardous for the environment (EEA 2019).

Waste

At the end of the nineteenth century, the American sociologist Thorsten Veblen described fashion waste as a distinctive attribute of the wealthy class in his renowned book, *The Theory of the Leisure Class* (1899). However, this paradigm has changed over time, and accelerated from the prêt-à-porter fashion common during the 1970s. This growth is emblematic of the Anthropocene, thus transforming the entire sector and giving rise to the fast-fashion phenomenon (Ricchetti 2017). The average European

consumer currently discards about 11 kilograms (kg) of textiles per year. Some of this clothing may be reused at the end of life, but the majority ends up incinerated or in landfills.⁷ Today, despite professed eagerness for a circular economy approach, recycling rates are insufficient, with an estimated less than 1% of textiles worldwide being recycled and transformed into new products (EC 2020). Another issue in recyclability is the vast use of mixed fibers which are problematic for a circular flow of materials because they cannot be recycled profitably (Eppinger 2022). Yet, if, on one hand, the sector generates very high negative impacts due to synthetic and mixed fibers, on the other hand, progress toward more effective and sustainable solutions is to some degree evident and highlighted by the case studies presented in Table 1. Some countries have high collection rates for reuse and recycling, however, many of the salvaged garments are exported to developing countries that lack their own recovery infrastructure so clothing ultimately ends up in landfills or undergoing downcycling processes (Watson et al. 2016; EMF 2017).

Deadstock management is another environmental issue related to the end of life of textiles. Unfortunately, burning and destroying unsold goods became a common practice among fashion retailers starting in the 1980s due to overproduction caused by miscalculations of consumer-shopping habits (Napier and Sanguineti 2020). High-end fashion brands regularly adopt this practice to prevent clothes/fabrics from being sold at discount prices in an attempt to preserve their exclusivity. In the face of rising environmental concerns, companies are currently starting to abandon this practice and to seek alternatives to manage unsold stock. Improvements in data analytics are also contributing to more effective efforts to manage the complex challenges of traceability in the intricate supply chains that characterize this sector (Sugumaran and Sukumaran 2019).

Jacometti (2019) observes that the limits of the linear economy model appear clearly in the garment sector and industry experts and practitioners also highlight the need to move to a circular economy model. Fashion design will need to facilitate the transition toward a sustainable bioeconomy in which raw materials derived from renewable resources replace those obtained from nonrenewable ones such as fossil fuels. Progress on this front could contribute to overcoming the problems of the linear economy model predicated on “production-use-abandonment” (Jacometti 2019).

Successful efforts to mitigate the environmental problems inherent in the contemporary fashion industry will need a holistic view of the complex

supply chain (Moretto et al. 2018) and this undertaking reflects a need for shared responsibility of the entire textile sector. It will be necessary to redesign textile production and consumption patterns based on sustainable innovation and knowledge exchange (Luján-Ornelas et al. 2020).

State of the art

The previous section outlined the major social and environmental problems of the fashion industry. The broad spectrum of complexity shows the need for an all-encompassing design vision that considers the entire production chain and the entire life cycle of the product. The literature demonstrates an in-depth understanding of the main challenges, highlighting what to date have been weak and uneven responses by key stakeholders. However, it is already possible to outline a series of guidelines and good practices as illustrated in this section. We consider three primary actors for an effective transition toward a more socially and environmentally sustainable fashion industry: governments, apparel industry, and designers.

Governments

Governments are critical change agents in developing the circular economy. The nongovernmental organization (NGO) Circle Economy observes that “When it comes to a circular economy, we are all developing countries” since no country today can satisfy its people’s basic needs within the ecological boundaries of the planet.⁸ In March 2020, the European Commission adopted a New Circular Economy Action Plan (EC 2020), including an EU textile strategy suggesting initiatives to achieve the circularity goals. The action plan anticipated development of eco-design measures to ensure that textile products are fit for circularity: incentives for and access to reuse and repair services; support for product-as-service models, circular materials and production processes; demand for increased transparency through international cooperation; support to reach high levels of separate collection of textile waste and boosting the sorting, reusing, and recycling of textiles; and encouragement of regulatory measures such as extended producer responsibility.

Concerning the extensive use of synthetic fibers, the EU strategy for a circular economy provides crucial proposals for good practices to address microplastics such as labeling, standardization, certification, and regulatory measures, including plans to increase the capture of microplastics at all relevant stages of the life cycles of products. These initiatives emphasize the need to develop methods for

measuring unintentionally released microplastics and related environmental risks (EC 2020; EEA 2021).

Apparel industry

How is the fashion sector responding to its socio-environmental challenges? Some researchers argue that there is a lack of tools and studies to provide environmentally friendly materials, to highlight the complexity of the impacts generated by creative industries, and to provide sustainable material solutions (Cicconi 2020; Pereira et al. 2021).

Alongside policy makers, coalitions of fashion brands are starting to develop tools and guidelines for sustainable fashion. A key factor is creating knowledge and awareness among designers and firms from open-access resources. An example is the sustainable strategies toolkit and materials database provided by the Council of Fashion Designers of America, a trade association founded in 1962.⁹ The Sustainable Apparel Coalition has also developed tools like the Higg Materials Sustainability Index to improve understanding of the environmental impacts of different materials and processes in the textile industry. These frameworks are useful for overcoming the difficulties that brands and designers face in not having enough energy and resources to access relevant and trusted data (Pollini and Rognoli 2021; Luo et al. 2021).¹⁰

Also, consultancies for sustainable fashion are developing tools to address the needs of clients in a sustainable transition. One example is the “seven strategies” concept formulated by consultant Anna Brismar for her firm Green Strategy which specializes in circularity and sustainability for fashion.¹¹

The sustainability efforts of companies address circularity with diverse foci such as reuse, controlled and efficient recycling processes, sustainable design, and innovative materials. LVMH Group sells dead-stock of high-quality fabrics and leathers from the company’s fashion houses at competitive prices to encourage the creative reuse of materials.¹² Post-consumer recycling can also be a sustainable way to source local raw materials for new circular production and this approach requires identification of the recycled content and its state of wear. While the process is not simple, a project like Textile Lifecycles by the Finnish company Tauko demonstrates its feasibility.¹³ The clothing firm Rapanui has adopted a policy of material recovery that uses its old products to produce new ones. As the company explains on its website, “A pure material makes remanufacturing possible, and means products that are softer, and not harmful to the environment.”¹⁴ These examples highlight how the selection

of materials is critical for effective and valuable recycling and determines the future material cycles (Pollini and Rognoli 2021).

Another instance is Salvatore Ferragamo which in 2017 introduced for its capsule collection a material called Orange Fiber, a silky fiber derived from the wastes of Italian citrus fruits.¹⁵ In 2021, the company created a limited edition of the iconic Top Handle bag made from certified cork, natural fibers, and finishing, while the zipper and thread were from certified recycled polyester. Materials are also critical in design for disassembly. Resortecs® produces a particular sewing thread that melts quickly to enable garment recycling during automatic demanufacturing of apparel at an industrial scale.¹⁶

Another central challenge for the fashion sector is corporate social responsibility which is closely linked to the social risks in the supply chain regarding material sourcing and manufacturing activities. To manage social issues, the actors operating in the supply chain can apply three main actions: compliance, supplier development, and communication practices. Unfortunately, these methods have not always been effective in finding a balance between economic self-interest and the costs of implementing social standards (Köksal, and Strähle 2021). The website Fashion Checker (by the Clean Clothes Campaign and funded by the European Union) tracks the social commitment of companies and in 2020 reported that 93% of surveyed brands were not paying garment workers a living wage.¹⁷ Excessive working hours, unsafe conditions, and violence are common in garment factories and the Clean Clothes Campaign reports that the COVID-19 pandemic has made the situation worse.¹⁸ While most brands cannot yet provide guarantees and transparency through the long and intricate supply chain, some pioneers such as Known Supply have made their simple and visible supply chain the company’s greatest strength.¹⁹ This brand is a partner of Fair Trade Certified™, thereby creating direct trade relationships. Moreover, the website allows customers to determine who produced particular items using a “Meet the Makers” section.

Designers

In addition to governments and the apparel industry, designers are becoming more aware of their role in addressing sustainability issues. For this reason, there has been a growing interest in more conscious design and production techniques (Rognoli, and Ayala-Garcia 2019; Barati, and Karana 2019). Many designers started experimenting with alternative materials, bringing materials research into the focus of their projects, if not the purpose of the projects

themselves (Rognoli et al. 2015; Lee 2015; Solanki 2018; Franklin and Till 2019). The experimentation, development, and proposals of designers for sustainable material alternatives are now stimulating new commitments on the part of both individuals and firms and increasing critical thinking (Migliore 2019; Rognoli, Ayala-Garcia, and Bengo 2017). These activities involve the development of samples, prototypes, and collections that demonstrate the possibility of new material paths and novel sustainable production and consumption models. Fashion and product designers in particular are demonstrating that is possible to go beyond the usual limits of their discipline in testing materials; hybridizing with science, engineering, and biotechnology; and embracing an increasingly transdisciplinary approach (Oxman 2016; Langella 2019; Migliore 2019). If traditional form-focused design previously determined designers' limited knowledge of materials, a change is now taking place through the direct action impelled by the designers themselves. They are engaged in the conceptualization of material, where the material becomes the real project driver (Karana et al. 2015; Bak-Andersen 2018), a shift also noticed among fashion designers (Ribul, Goldsworthy, and Collet 2021).

Key concepts of eco-design and the circular economy, such as design for durability, reparability, and reuse, are increasingly being adopted and integrated into design strategies. The Togolese designer, Amah Ayivi, has created high-fashion clothes to sell to Western consumers that are made from the recovery of clothes destined for charity and secondhand markets.²⁰ Although this approach may seem contradictory, it tackles the problem of tons of garments that cannot be reused (for example, winter suits) and which would otherwise become delocalized waste. Moreover, this operation aims to promote greater space for the African textile sector, which is often overwhelmed by secondhand clothes. Applying the reuse strategy to extend the lifespan of textiles, Ayivi also relies on a valuable esthetic based on luxury collections.

Wastes derived from the most diverse sectors are being used as raw materials (Cleries et al. 2021). Many designers prefer working with bio-based and renewable resources as alternatives to materials that are made of plastic. One example is the project *Repearls*, developed in 2021 by Margherita Grassi to tackle the impacts of embellishments like plastic buttons and beads, for which she developed a pearl-like material from the waste of oyster shells.²¹

Another emerging trend is the involvement of living organisms in the material-fabrication process. Here, the transdisciplinary approach is fundamental, and the prospects for sustainable innovation are

those of biotechnologies and the bioeconomy. More and more case studies are referring to materials, fabrics, and processes derived from fungi, algae, or bacteria. For example, Suzanne Lee, a pioneer in the fashion industry with Biocouture, was the first designer to offer a speculative collection made of bacterial cellulose starting around 2008–2010 and still under development. Her early DIY experimentation with the material (begun in approximately 2004) was the beginning of a long journey that sees her today as Chief Creative Officer at Modern Meadow, one of the biotechnology companies intriguing the fashion sector with exciting offers to seek better standards of sustainability with the help of biology.²²

We are especially keen in this article to highlight the integration of natural agents into materials innovation as one of design community's most disruptive responses. The following section focuses on the design approaches supporting this transition in fashion, defining the materials and organisms involved in this new emerging materiality.

Approaches enabling designers

In parallel with increased attention to the management of materials within the life cycle of products, designers are developing in research labs and startup companies new applications of bio-based materials embedded in circular models. However, in fashion, new materials are usually aimed at replacing or mimicking established fabrics (e.g., there is a big focus on creating leather replacements). Rather than creating novel applications, new materials are often positioned by imitating the characteristics of other materials. It remains challenging to position them through their unique qualities (Karana et al. 2015) and uses, precisely because they still do not have a definite identity and experience with them is limited (Hildebrandt, Thrän, and Bezama 2021).

A focus on the materials experience offers alternatives where designers can be sensitized to the unique qualities of novel materials, potentially leading to meaningful applications. Karana, Pedgley, and Rognoli (2015) build on the proposition by Manzini (1986) that designers need to know what materials are and what they do. They suggest that designers need to ask: What does it express? What does it elicit from us? What does it make us do? These questions help designers go beyond understanding the material and expand into the experiential aspects of what materials can do.

The role of the materials experience in sustainability has already been investigated using the concept of "Materially Yours" (Karana, Giaccardi, and Rognoli 2017) which indicates strategies for using

materials at different experiential levels to assist in the design of longer-lasting products. By expanding the territories of the materials experience, the aim is that it will be possible to improve the ability of designers to address environmental considerations.

The growing impact of human artifacts (and their waste), and the ever-increasing pressure on material resources, requires a change in our relationship with the artifacts themselves, including the materials of which they are made. Considering the expanded territories of materials and design (Pedgley, Rognoli, and Karana 2021), material skills are (re)gaining importance in design. The bodily experience of the material is irreplaceable even if the history of design shows how the very act of designing marked the separation between the materials and the project (Bak-Andersen 2021). In fact, the arrival of industrial design brought a division between intent (design) and making (production). Using the concept of the materials experience (Karana, Pedgley, and Rognoli 2015; Giaccardi and Karana 2015), as well as the Material Driven Design method (Karana et al. 2015), it is possible to design the material by focusing on the experiential dimension.²³ Furthermore, with the DIY-Materials approach (Rognoli et al. 2015; Rognoli, and Ayala-Garcia 2021), experimentation and tinkering restore the physical separation between the designer and the materials.²⁴ Indeed, with DIY-Materials, designers, who are not looking at materials that someone has already designed and developed, are motivated to inquire about and challenge themselves by experimenting and thinking about their own design of materials. From this standpoint, many authors agree that material explorations and material tinkering are no less important than materials selection (Parisi, Rognoli, and Sonneveld 2017; Rognoli, and Parisi 2021; Bak-Andersen 2021). In other words, in the contemporary material atelier, designers and designers-in-training become acquainted with materials in effective ways (Pedgley, Rognoli, and Karana 2021).

A significant motivation for encouraging designers to undertake the DIY-Materials approach is to find more sustainable and eco-friendly material solutions. However, using this methodology does not guarantee a sustainable material outcome at the end of experimentation. Instead, it is necessary to consider that such an approach leads the designers to make decisions that help them improve their sensitivity toward sustainability challenges as they become increasingly aware of their role as facilitators and pursuers of sustainable solutions.

The environmental impact of DIY-Materials has not yet been studied in-depth, and although superficially demonstrated, scholars describe a positive relationship between this approach and

sustainability and identify its potential to find more sustainable material solutions (Rognoli and Ayala-Garcia 2021; Bak-Andersen 2021; Rognoli, Santulli, and Pollini 2017; Fadzli, Aurisicchio, and Baxter 2017; Alarcón and Llorens 2018; Rognoli, Ayala-Garcia, and Pollini 2021; Caliendo, Langella, and Santulli 2019; Karana et al. 2017).

In the fashion sector, several examples of materials developed from waste, bio-based and organic sources, and living organisms testify to the importance of experimentation and tinkering. Furthermore, in these cases, the designer is the one who visualizes, facilitates, and provides the solution (designer as the solution provider, Bak-Andersen 2021; designer as the facilitator, Manzini 2014) in the specific material solutions that can inspire and initiate the development of the material for industrial production.

Given the observed paradigm shift toward the consolidation of bio-fabrication and the cross-fertilization of biology with design (Zhou et al. 2021), the designer can also enable the creation of materials from living organisms. This can bring new sustainable solutions and different forms of expression for design, and specifically for fashion. The following section introduces the bio-fabrication of materials as a possible alternative to the contemporary manufacturing model based on intense consumption of energy and materials. Such a change would be welcome given its alignment with the principles of biology and circularity. Furthermore, as many scholars claim (see, e.g., Collet 2018; Kääriäinen and Niinimäki 2019; Kamiński et al. 2020), bio-fabrication, and bio-based materials in general, could represent a satisfactory response to the environmental and social problems of the fashion sector.

Introducing bio-fabricated materials

Historically, human productions, including textiles, have been deeply connected with the natural world. After decades of industrial models and oil-based materials, a rediscovery of natural resources is being driven by the will to produce within the limits of the planet's capabilities. Today, while the sustainable fashion landscape is dealing with terms and definitions such as slow, ethical, green, and eco-fashion (Brydges et al. 2020), new materials trends are emerging and affecting the fashion sector.

A newfound interest in bio-based resources pushes material designers to develop new and/or rediscovered material solutions from natural resources and to design around material flows. Recently, designers have also begun to perceive organic waste as a source of valuable raw materials to be experimented with to develop new textiles (e.g., Vegea,

Orange Fiber), following a circular and bioeconomy model (Collet 2018).²⁵ Besides newly circular made-from-waste and bio-based textiles, living organisms integrated as functional components in designing new materials offer a new sustainable opportunity.

This trend is associated with the rise of Biodesign (Myers 2014), a radical approach born from the cross-pollination between biology and design, where materials are bio-fabricated and obtained from organisms such as bacteria, enzymes, algae, mycelium, and others. In Biodesign, materials gain a predominant role and they are made of, with, or from living organisms (Ginsberg and Chieza 2018) that engage in morphogenesis: from more passively growing in a given shape to more actively co-designing the final object or material (Collet 2013; Camere and Karana 2018; Karana, Barati, and Giaccardi 2020).

Although the term “bio-fabrication” originated in the medical sector, Mironov and colleagues in 2009 widened its definition to biotechnology and defined it as “the production of complex living and non-living biological products from raw materials such as living cells, molecules, extracellular matrices, and biomaterials” (Mironov et al. 2009). In 2020, the report *Understanding “Bio” Materials Innovations* (Lee et al. 2020) focused on the fashion sector, stating that “bio-fabrication technologies are evolving and extending into application areas, including textiles for fashion.” The potential for the fashion sector derives from the possibility that different organisms can self-grow into fibers, tissues, or dyes, using life-friendly chemistry and processes typical of biological growth. This article focuses on those materials produced by living cells and organisms such as bacteria, yeast, algae, mycelium, and plants, and particularly on their potential application for the fashion sector and textile industry.

The origins of Biodesign are characterized by a DIY approach and open-source philosophy (Elsacker et al. 2020) and the first dedicated study paths have become established. The case studies of bio-designed materials were initially experimental and related to speculative design (Aldersey-Williams et al. 2008; Myers 2014), but it is now not uncommon for a designer’s DIY approach to lead to establishment of a successful company in the biotechnology field such as Ecovative, Mogu, Mycoworks and Modern Meadow.²⁶ The desire of the designers behind these companies (or with similar inclination) for sustainable and radical solutions led to a first-round (primarily speculative) of exploratory research to test the potential of living biological resources to replace oil-based and polluting ones. The visions traced by the first experimental prototypes were then scaled and experimented

with further, leading to today’s first examples of bio-fabricated materials applied to the world of textiles.

With various degrees of biotechnological maturity, today, it is possible to consider the idea of dyeing fabrics with less water and fewer chemicals, using bacteria or producing alternatives to animal leather, such as fungi or bacterial cellulose created by a symbiosis of bacteria and yeasts, reducing environmental and ethical problems related to the tanning of animal leather and animal welfare. For instance, it is possible to weave and dye with algae. In short, what seemed to be highly speculative propositions ten years ago are slowly approaching the market, thanks to advancements in biotechnology.

Bio-fabricated materials are starting to stimulate a highly engaged audience due to the sustainable features associated with their biological origin and underlying techniques. In parallel with the material experiments of designers, and sometimes as a direct consequence of these activities, the biotechnology sector is investing heavily to increase the potential of these organisms as alternative sustainable materials (Matthews et al. 2019).²⁷ Bio-fabrication techniques also contribute to transforming society by limiting the exploitation of child and female labor that is widespread in the traditional production of textiles in the global South. Indeed, bio-manufactured materials could be an excellent opportunity for innovation and renewal from workforce training, making it more advanced and updated (Miehe et al. 2020; Ahmad 2020). Furthermore, the DIY culture, including DIY with biology (thus incorporating DIY bio-fabrication techniques), due to its intrinsic nature, supports the model of distributed micro-production (Bianchini, and Maffei 2013), drawing on local sources and fostering bio-based and circular solutions (Devadas et al. 2021; Meyer et al. 2020; Provin et al. 2021). Moreover, this approach, initiated through DIY-Materials investigations, can foster self-sustaining models in remote places (Palacios et al. 2020).

Biomaterials can empower local production and give rise to new alternative and sustainable production methods that support local producers by creating resilient socio-technical systems based on hybridized social and technological innovation. Such developments are determined by interactions undertaken directly by the interested parties (in a bottom-up approach), and different types of interventions by institutions, civic organizations, and companies (from a top-down approach) often support them (Manzini 2011).

A trigger for designers and a push from the market derives from the prospect that these materials have the potential to create a radical shift to more

sustainable fashion. The speed of growth of these organisms denotes them as rapidly renewable (Camere and Karana 2018). The production processes use life-friendly chemistry, do not require much space compared to plant or animal harvesting (Bhat and Bhat 2011), use less energy than synthetic processes, and require smaller amounts of water and other resources. However, due to the complexity of a product's life cycle, many factors can influence the overall impact of a material or product. In life cycle design, the material must be selected to comply with the design requirements imposed by the functional unit to achieve a minimum impact. Life cycle analysis (LCA) is the most reliable methodology for comparing multiple materials as it can show the different impacts occurring throughout an object's life cycle. The first studies comparing the LCAs of bio-based and bio-fabricated materials highlighted the hidden implications of these alternatives (Hildebrandt et al. 2021). When analysts compared leather-like bio-based and bio-fabricated materials to animal-based leather, the impact of the bio-based alternatives entailed the use of land, water, and chemicals to harvest the vegetable fibers; moreover, the bacterial cellulose impacts were related to the feedstock source and the finishing treatment. These variables need to be thoroughly evaluated with a forward-looking approach when upscaling the production of bio-based and bio-fabricated materials.

Moreover, a study by Hildebrandt et al. (2021) highlights that alternative bio-based leather substitutes can contribute to relative environmental advantages in impact reduction (especially concerning CO₂ emissions), but only if the material substitution is coupled with less frequent product replacement. This means that a profound cultural transformation is needed to achieve sustainability goals. When trying to reduce the impact of human production, behavioral change is significant and influential in terms of economic and design strategies (Ricchetti 2017). This is also true for bio-fabricated materials (Collet 2018; Hildebrandt et al. 2021).

In addition, some of the key impacts of materials highlighted in this article are among the main features influencing users' tendencies to retain their products for longer periods of time, as suggested by the Materially Yours concept discussed above. Narratives and identity, among other factors, are important for emotional, long-lasting designs and can be used to develop strategies that increase product attachment (Haines-Gadd et al. 2018).

The product's identity and personality (concepts further addressed in the following sections) can reinforce users' beliefs, including creating connections with communities, for example, if the material

is produced locally and grown on wastes from proximate sources. The narrative behind bio-fabricated materials can evoke a radical idea of sustainability in balancing ancient knowledge (e.g., fermenting processes) and future innovation (e.g., biotechnologies). Moreover, these material narratives can shift the collective imagination about the future of products, systems, and processes as they are based more on biological regeneration than on the depletion of nonrenewable resources (Chapman 2021).

Bio-based and bio-fabricated material cases for fashion

As this article has shown so far, textiles made of bio-based and bio-fabricated materials, following a long-term dominance of well-known synthetic and natural fibers, are currently seen as a novel option for sustainable purposes, despite the development of biosynthetic fibers dating back to the late 1800s (Textile Exchange 2018). This long history, combined with the recent interest of designers, has resulted in a plethora of bio-based and bio-fabricated materials available today with unique qualities and characteristics that are still being explored, comprehended, and defined.

The current understandings and experiences emergent with these novel materials are influenced by applications and communication that help define the social space they will occupy. Given that many of these nascent materials remain niche products and are distant from the public, it is especially crucial to examine them further through a case-study analysis that helps to highlight the opportunities and challenges for the widespread adoption of these materials. Additionally, decisions in terminology need to be balanced, on one hand, between scientific accuracy and, on the other hand, consumers' understanding, market strategies, and brand-positioning opportunities (Lee et al. 2020; Ahmad 2020; D'Olivio and Karana 2021).

To restate the purposes of this article, the objective is to build a panorama of possible alternative bio-based and bio-fabricated materials to favor a lasting and effective transition toward more sustainable fashion. We aim to provide more information on the origin and potential of these emerging materials to improve awareness of the benefits that will likely come through societal acceptance and to further support the design community with new tools to appreciate and apply them in the fashion industry for more sustainable results. Furthermore, the article highlights how these evolving approaches to material design can positively contribute to the proliferation of alternative and sustainable materials for fashion. To serve this purpose, we have developed

the concept of “materials biography,” outlining a set of categories to better define these new materials and to examine their peculiar features by supporting the material narrative and raising awareness among designers about the range of their applications and environmental characteristics.

Methods

We selected 24 material cases to further explore current understandings that have emerged with novel bio-based and bio-fabricated materials. We analyzed them in terms of common and meaningful information that could help generate appreciation and position their materials biographies. These characterizations include a detailed description of each material’s life and highlight the attributes that we consider to be most significant.

This study was carried out through desk research to collect, select, and analyze cases of bio-based and bio-fabricated materials for the fashion sector. Between February and May 2021, we undertook an exhaustive search for new materials through scientific journals using leading academic databases such as Scopus and Google Scholar. In addition, we completed an exploration of grey literature such as fashion and design reports, magazines, blogs, textile manufacturer’s and designer’s websites, and related press releases. The keywords used for the search of materials cases were “bio-fabricated materials,” “growing materials,” “bio-fabrication in fashion,” “bio-based materials in fashion,” and “bio-based materials in apparel.”

Criteria for selection

There were two primary eligibility criteria for the cases: (1) the selected materials had to be at least at a proof-of-concept stage and (2) their main field of application had to be the fashion sector. Biotechnology offers exciting opportunities for novel and more sustainable alternatives for the design and manufacturing of products. One of the most promising approaches is developing materials from living organisms such as fungi and bacteria (Camere and Karana 2018; Collet 2018; Collet 2017). Thus, the research presented here focuses on selected cases that best represent the potential of these bio-based and bio-fabricated materials for future designs that are consistent with humankind’s need for a sustainable transition. As previously mentioned, the definition of “fabrication of materials by living organisms” (Groll et al. 2016) seems the most suitable to frame those materials processes involving living organisms. Thus, all the examples collected for this study have been bio-fabricated by living

organisms. The typology of organisms generating the material was one of the observed characteristics and this feature also helped group the cases, as shown in Figure 1.

The design and development period neither discriminated against the eligibility of cases for this study nor their approach, which is sometimes speculative but aimed at a vision of future feasibility. In the field of bio-fabrication, a considerable amount of research is currently underway to develop new materials. In addition, in the fashion sector, many alternative bio-based materials (for example, leather substitutes) are still in the research stage. Accordingly, we have included those cases that were at least at a proof-of-concept stage but will still require time before they are potentially commercially viable. In contrast, others are already on the market, albeit often with limited production. This study considered materials under development since the early 2000s to ensure that material innovations relevant to the focus of this article were included and to provide an overview of the most important cases.

We need to note that public information about these new materials is oftentimes still limited. Recent academic research in the field also relies heavily on desk research to understand them (D’Olivo and Karana 2021) and many of the sources come directly from the manufacturer or related commercial partners. While having primary sources of data is very valuable, investigating how companies portray these materials for marketing and other business purposes is also critical.

A first analysis of the material cases

A preliminary analysis of the cases proved necessary to bring out some fundamental aspects helpful in developing the findings. Table 1 reports the selected cases, highlighting some criteria employed for our initial analysis. Apart from the name of the material, we collected the following data to further deepen knowledge of these emerging materials. The first step was to group the material cases according to the organism involved in their origin: bacteria, yeast, algae, mycelium, and plants (Figure 1). The bio-based origin cannot be translated into products’ biodegradable end of life because this depends on the manufacturing process which the relevant company does not always declare. For this reason, the second criteria for organizing the data was the end of life of these materials which we found to be unknown in many cases. We also collected the range of applications within the fashion-production processes, distinguishing between textiles, dyeing biotechnologies, application in accessories, and so forth.

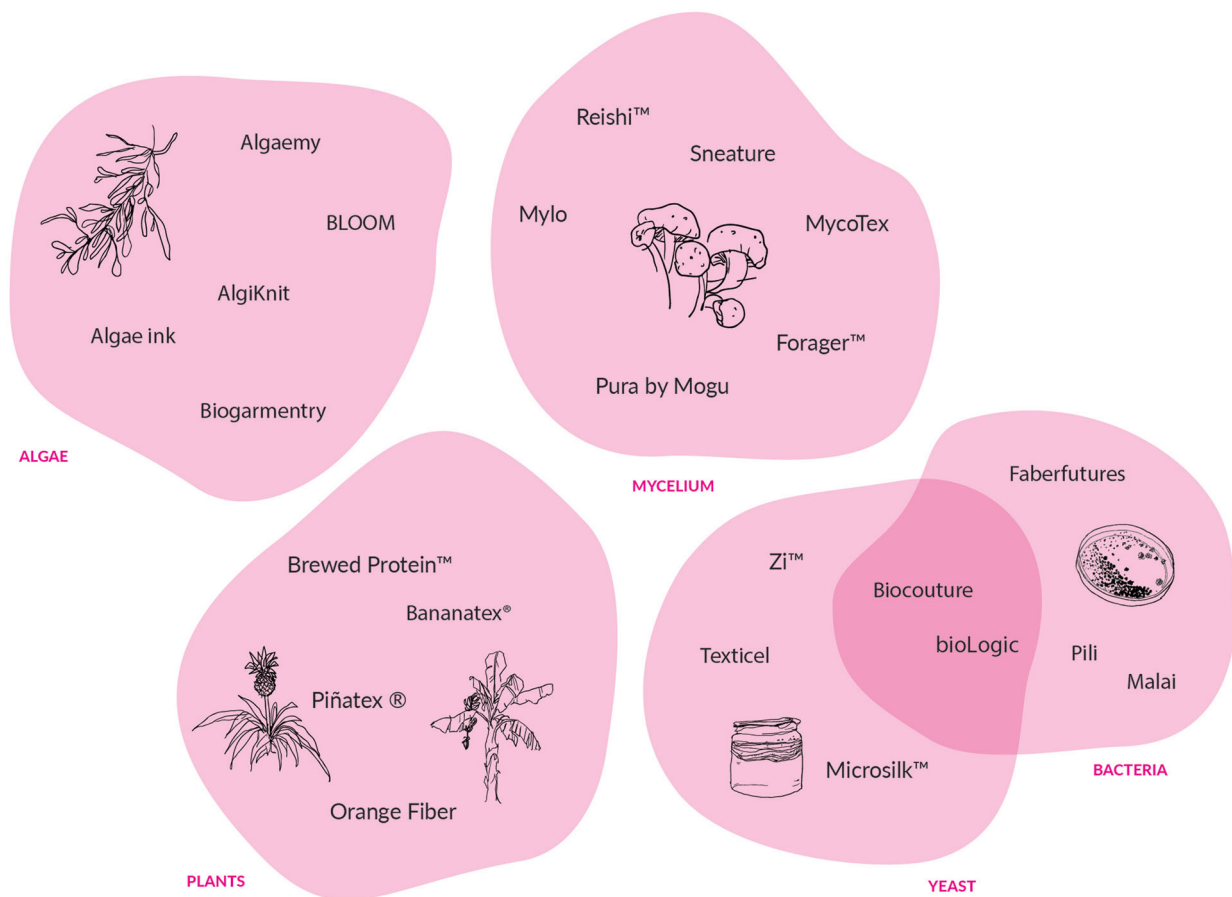


Figure 1. Groups of material cases according to their origin.

The study revealed that many of these novel materials were positioned as potential replacements for common and less sustainable materials currently used in the fashion sector. Therefore, to display the cases we created a cluster named “mimics” (Table 1) aimed at creating parallel comparison with the type of material that the new one is being designed to replace and, in some ways, “imitate” esthetically.

We collected information on the locations of the associated companies to identify the hotspots of this biotechnology revolution in the fashion sector. The study showed significant involvement of firms based in Europe and the United States as well as a few in Brazil, Japan, Thailand, and the Philippines. Finally, we assembled data on the main processes used to produce and bio-fabricate these materials. Many of these materials require a lab environment, while others follow more traditional paths.

The following section provides an in-depth description of each organism in the bio-fabrication process of the selected cases.

Bacteria

Most cases of bio-manufactured materials originating from bacteria are made with bacterial cellulose from various bacterial strains. *Acetobacter* bacteria which

present favorable physical and mechanical properties for applications in fashion have received the most attention in the design field (Rathinamoorthy and Kiruba 2022). As stated, the pioneer researcher in this domain is Suzanne Lee. In 2004, she started growing bacterial cellulose in a tea and sugar static culture medium and applied it to a leather-like jacket. This process is still the most popular alternative for researchers involved in producing cellulose sheets for fashion applications (Rathinamoorthy, and Kiruba 2022; Da Silva et al. 2021; Domskiene, Sederaviciute, and Simonaityte 2019). The weakness of this process is the drying part which produces a loss of flexibility and breathability generated by structural disintegration (Rathinamoorthy and Kiruba 2022), as well as the difficulty of finding suitable finishes that could counter these problems (Hildebrandt, Thrän, and Bezama 2021). Several researchers are looking for solutions to these obstacles (Sederavičiūtė et al. 2022).

A second approach involves Malai which is a bio-composite material made from bacterial cellulose that is grown on agricultural waste sourced from the coconut industry in Southern India.²⁸ The company collects the waste-coconut water from local farmers and processing units and feeds bacterial cellulose production. One small coconut-processing

Table 1. Final selection of material case studies.

	MATERIAL	END OF LIFE	APPLICATION	MIMICS	LOCATION	PROCESS
 ALGAE	Algae ink™	Compostable	Dye	Conventional dye	United Kingdom	Made from algae pulp
	Algaemy	Unknown	Dye	Conventional dye	Germany	Made from microalgae
	AlgiKnit	Biodegradable	Yarn	Conventional yarn	USA	Unknown
	Biogarmentry	Unknown	Clothes	Conventional fabric	Netherlands	Lab made
	BLOOM	Non-recyclable	Accessories	Rubber	USA	Unknown
 MYCELIUM	Reishi™	Biodegradable	Accessories	Leather	USA	Lab made
	Forager™	Unknown	Accessories	Leather	USA	Lab made
	Pura by Mogu	Unknown	Accessories	Leather	Italy	Lab made
	MycotEX®	Unknown	Accessories/ Clothes	Leather	Netherlands	3D manufacturing
	Mylo™	Non-recyclable	Accessories	Leather	USA	Lab made
 BACTERIA	Malai	Unknown	Accessories	Leather	India	Bacteria grown from coconut water
	Pili	Unknown	Dye	Conventional dye	France	Fermentation
	Faberfutures	Unknown	Dye	Conventional dye	United Kingdom	Fermentation
	Texticel	Compostable	Accessories	Leather	Brazil	Lab made
BACTERIA & YEAST	Biocouture	Compostable	Accessories/ Clothes	Leather	USA	Lab made
	bioLogic	Non-recyclable	Accessories	Leather	USA	Lab made
 YEAST	Microsilk™	Biodegradable	Clothes	Silk	USA	Protein made from yeast
	Texticel	Compostable	Accessories	Leather	Brazil	Lab made
	Biocouture	Compostable	Accessories/ Clothes	Leather	USA	Lab made
 PLANTS	Piñatex®	Partially biodegradable	Accessories	Leather	United Kingdom / Philippines	Coated non-woven fabric
	Brewed Protein™	Testing stage	Clothes	Wool	Japan/ Thailand	Fermentation
	Orange Fiber	Biodegradable	Clothes	Lyocell	Italy	Cellulose extraction
	SweetFoam™	Biodegradable	Accessories/ Footwear	Rubber	Brazil	Cellulose extraction
	Bananatex®	Biodegradable	Accessories	Canvas	Switzerland / Taiwan/ Philippines	Cellulose extraction

unit can collect 4,000 liters of water per day which can produce 320 square meters (m²) of Malai. The resulting material is comparable to leather or paper and is flexible, durable, and water-resistant.

A third route being explored with bacteria entails the creation of dyes. Currently, several companies are using DNA circuits to produce colorants in microorganisms (such as bacteria). These companies include Pili (France), Colorifix (UK), and Ginkgo

Bioworks (United States).²⁹ The technology is challenging and there is often a drastically different pathway for each color. Thus, the technology is only now emerging and the range of colors is minimal.

Yeast

Synthetic biology is the core technology underlying most of the materials that originate from yeast.

Current research involves programming these microorganisms to produce something that they do not usually produce or something in greater quantity. The outputs of such processes are incredibly variable, meaning that the material opportunities are vast through this route. Examples of companies applying this technology in consumer fashion include Bolt Threads (Microsilk) and Modern Meadow (Zi).

Bolt Threads employs genetically modified yeast to produce a silk-like material and aims to scale this approach to make consumer products. Inspired by the properties of spider silk, Microsilk is an attempt to emulate its high tensile strength, elasticity, durability, and softness, creating an enhanced rayon through bio-engineering (i.e., fermentation, using yeast, sugar, and water).³⁰ The company claims that this is achieved with less environmental impact than the usual textile-manufacturing processes with the additional benefit that the material can biodegrade at the end of life.

Modern Meadow, launched in 2012 (Mainwaring 2012), created a range of bio-fabricated materials named Zoa that are design-driven by function and sustainability. The first collection of materials named ZiTM uses proteins (genetically modified yeast) and bio-based polymers that create what the brand calls a Bio-AlloyTM and results in a leather-like material. In terms of performance, the brand declares that ZiTM is resistant to abrasion and water, is durable, and holds shape.³¹

Algae

Edward Stanford first discovered Alginate in 1881. Since being commercialized in 1927, Alginate has become the most abundant marine biopolymer and, next to cellulose, the most popular biopolymer in the world. It is widely used in the medical, food, textile, material, reactive dye, and printing industries because of its water-retaining, gelling, and stabilizing properties. AlgiKnit, Inc. is a biomaterials company integrating science and design into textile production, creating durable yet degradable yarns from kelp (a type of seaweed or macroalgae).³² The yarns can be applied across the fashion industry and in packaging and home furnishing. The company praises the material's associated benefits: it is grown in the ocean (does not use upland, pesticides, or fertilizers), and its CO₂ capture purifies the surrounding water; however, more studies are needed to clarify the environmental and social advantages of such production.

Vollebak makes T-shirts from lyocell (pulped eucalyptus and beech from sustainably managed forests) and the print on them comes from algae grown

in bioreactors which is biodegradable.³³ This garment will decompose in compost or a landfill in twelve weeks. The company emphasizes that this is a regular T-shirt, the only difference being that all the materials going into making it are “grown by nature” and can “go back to nature” at the end of life. Green algae (spirulina) are used for the dyeing, and as it is a plant dye, it does not use other chemicals, only carotenoids and chlorophylls occurring in the algae. It is no longer alive when applied to the T-shirt; its color will change due to oxidation in contact with air (i.e., it is expected that the color will fade with time). Similarly, Blond and Bieber's design studio uses algae to create colorful dyes for textile printing that change color when exposed to sunlight, creating bright and dynamic colors.³⁴

Mycelium

Mycelium constitutes the principal vegetative portion of a fungus. It consists of networks of branching microfilaments containing mixtures of cellulose and chitin. These interlinking branches can form very robust structures. The manufacturing process (mostly for the production of packaging) involves combining waste materials (agricultural/plant-based) with mycelium (vegetative fungus). This mixture is placed in molds and the mycelium grows to occupy the mold to form the desired shape. The process takes about one week (Karana et al. 2018; Arifin, and Yusuf 2013; Collet 2017; Williams and Collet 2021).

Ecovative has emerged as the leader in manufacturing with mycelium (first provisional patent 2006, fulfilled in 2016). The company has developed applications in foam and bulk-material development as well as textiles. The company has formulated applications in foam and bulk-material development as well as textiles. It created MycoFlexTM using pure mycelium foam to produce compositions for diverse applications include leather-like materials. The material is heat resistant, insulating, hydrophobic, breathable, and strong.³⁵

Bolt Threads (founded in 2009) is one of the pioneers in developing a mycelium-based leather substitute. It was first seen in an application in their Mylo Bag, pre-sold on Kickstarter in the summer of 2018.³⁶ The material Mylo has been optimized in the intervening years and applied in different concept pieces by Adidas (Stan Smith MyloTM) and Stella McCartney garments (top and trousers in March 2021).³⁷

Mogu, a European-based company, also developed a Pura Flex leather substitute using mycelium and bio-fabrication technology.³⁸ Mogu employs non-genetically modified organisms (non-GMO)

and non-allergenic fungal strains, which do not release any spores throughout the whole production process. The materials are durable and will only degrade in the right conditions at their final disposal, meaning that the material is biodegradable and can be broken down and re-assimilated back into the natural environment but it requires specific processes for degradation.

Plants

Plant-derived materials rely on growing plants, the agricultural industry, and their byproducts (Shogren et al. 2019). While they can offer more sustainable alternatives to current materials it is essential to consider land use and prioritization of food systems when opting for such alternatives.

Piñatex[®] is a non-woven textile made from waste pineapple-leaf fiber coated with resin to mimic a leather look and feel.³⁹ The leaves are the byproduct of existing agriculture and their use creates an additional income stream for farming communities. Piñatex[®] is a natural, sustainably sourced, cruelty-free material. It first appeared in 2014 and is now being applied to products (e.g., shoes and bags) available to the consumer.

SweetFoamTM was developed in a partnership between the shoe brand Allbirds and Braskem and launched in 2018. It is a bio-based renewable resin⁴⁰ and Braskem has referred to the product as a “renewable bio-based EVA resin (ethylene-vinyl acetate copolymer)” to communicate the properties and applications of this material.⁴¹ This material is commercially available in Allbirds sports shoes.

Materials biography as a metaphor to strengthen the identity of novel materials

The concept of identity with reference to human beings is a complex and debated notion, especially in the social sciences. Today it acquires an even more significant role since society and technologies allow multiple identities for a single individual (for example, physical and digital identity) which creates more nuances to an already tricky concept.

The identity of materials is strictly connected with their acceptance and, therefore, their adoption by designers, industries, and end-users. Issues pertaining to the identity of materials have already been introduced in the debate on material design; here scholars have tried to improve understanding of and experience with novel materials that have a weak identity by adopting different approaches—e.g., bio-based, bio-fabricated or waste-based materials are still at a proof-of-concept stage (Rognoli, Salvia, and Levi 2011; Veelaert et al. 2020; Du Bois

et al. 2021; Confente, Scarpi, and Russo 2020; Karana 2012).

Furthermore, recent research has highlighted a gap in the literature regarding how these materials can be presented to a broader audience (D’Olivo and Karana 2021). Therefore, this issue is timely and of interest to the practice of design from different points of view. As an example of the concept of identity associated with the material it is crucial to consider that it took humans almost 100 years to have a shared, recognizable, and acceptable idea of plastic derived from petroleum and manufactured into a previously unknown synthetic material. The design practice was fundamental for creating the identity of oil-based plastics: the identity emerged through studying the essential traits and improving the material experience connected to them (Bijker 1995; Rognoli and Santulli 2014; Manzini and Petrillo 1991). The significant characteristics of plastic’s identity that have achieved acceptance and broad applications are mainly connected to its “mutant and versatile” character—such biological associations are based on the material’s ability to mutate in shape, texture, and color due to its biological nature. However, ignoring several fundamental features of plastic materials has overshadowed some aspects that today, with hindsight, have become problematic, most notably its end of life. In studies of material culture within the social sciences, especially anthropology and sociology, the concept of the “object biography” has been defined as an analytical process that examines the life history of an artifact to “address how the social interactions that they involve people and objects create meaning” and to understand how these meanings change and are renegotiated through the life of an object (Gosden and Marshall 1999). Such a biography may include information on the genealogy of an object or its manufacture, use, possession, exchange, alteration, movement, and destruction or storage as obtained from a wide variety of sources. The concept of “object biography” relates to the notion of “product biography.” The notion of “product biography” as advanced by Gregson et al. (2010) is helpful for this conceptualization. The authors suggest defining products not as standalone creations but as “assemblages of materials that are stabilised and then transformed by consumers” (see also Spring and Araujo 2017). This notion of “product biography” encourages reflection on the nature of products, including their role and identity, which tend to be more relevant in a circular economy where materials and products “undergo refurbishment, remanufacturing, dismantling, re-use and recycling, and being subject to new forms of valuation and exchange” and cannot remain anonymous and stable



Mylo™	
Lifecycle:	Dead mycelium Renewable resource Single life cycle (not currently biodegradable)
Temporality:	~ Two weeks to grow Durability still unknown
Origin:	Mycelium, fungi kingdom from vertical farming
Process:	Lab grown mycelial cells
Identity:	Mimicks leather

Figure 2. Material-identity card example showing material-biography categories applied to a material case.

in user experiences in contrast to a linear take-make-dispose model (Spring and Araujo 2017). They, too, become worthy of scrutiny in choice, care during use, and responsibility at the end of life.

In addition, the circular economy literature offers critical insights into individual biographical qualities of materials and leads to the conceptualization of a taxonomy to better frame them in a material-identity card (Figure 2). Two propositions have emerged at the material level for operationalizing important aspects of circular economy principles: “material passport” and “material narratives” or storytelling.

Thomas Rau and Sabine Oberhuber, in their book *Material Matters* (2019), highlight the importance of a “material passport” for the sustainable management of material flows in circular economies, facilitating materials-life extension while keeping their maximum value for as long as possible. They suggest that the collection of data on the material is helpful to have a picture of the physical reality: the material passport that they designed in 2011 records an accurate inventory of all the materials, components, and raw sources used in a product or building, along with information on their location. For them, each identity gives the object/material to which it is connected “a significant, unique, and unrepeatable character... suggesting the idea that it is something that must not be lost and that must be protected.” This is another example of how biographical information can positively contribute to the sustainable management of materials. However, because this is a novel proposition there is not yet an agreed-upon standard determining the requirements for material passports. Importantly, the recent *Proposal for Ecodesign for Sustainable Products Regulation* (EC 2022) released at the end of March 2022 also includes a recommendation to create a digital product passport to electronically register, process, and share product-related information

among supply-chain businesses, governmental authorities, and consumers.⁴²

Also important is the concept of material narratives which is based on storytelling techniques and is critical for materials acceptance (Machgeels 2018; Lambert and Speed 2017). It is used to enable designers, companies, and users to understand the materials before they experience them, given that often material samples are not readily available.

We endorse the concept of a “materials biography” to bring the notion of an “object biography” or “product biography” to the material level and for it to be used as a valuable tool to derive categories of materials biographies, therefore fostering broader and quicker acceptance and application of more sustainable materials in the fashion sector.

While the material passport focuses on traceable data about materials and the material narratives concentrate on communication as a marketing tool, the concept of “materials biography” relies on five material-biography categories that we deem to be more relevant during the early stages of material development. The categories serve primarily as a first acknowledgement of the material origin and main characteristics which we argue are unique to each new material: life cycle, temporality, origin, process, and identity (each of these items is explained in greater detail below). These categories can be explored when developing awareness of these novel materials, especially bio-based and bio-fabricated materials for the fashion industry.

Although we described the pervasiveness of bio-materials earlier in this article, most of the materials reported here are new, and still unfamiliar to the consumer. Therefore, these materials require stronger identities to help shape and develop users’ perception of their value, quality, durability, and desirability. Still, it is critical to acknowledge that storytelling is a central marketing tool in the

“content economy,” that is an economic system where people and organizations produce, distribute, exchange, and consume digital content products and services, as a result of the Internet and Internet-based technologies (González-Romo, García-Medina, and Romero 2017). Because the materials are still in their very early stages of entering the market, all information is attributable to the communication efforts coming from material-manufacturing companies, fashion brands, and their collaborators.

During the course of conducting the current study, we came to realize that the information about many material cases was inconsistent, leaving many blank spaces in the original spreadsheet (Table 1) and making it more challenging to compare materials and discuss them in common groups or categories. It was particularly the case when dealing with information about material production, the current readiness status of products, and their end of life. We could likely have predicted that this would be the case given that most of these materials are at different stages of production and that, even under patents, companies in these phases are generally very vague about the details of their products. We found that even designers and companies who had not yet registered their products were keen to protect their intellectual property and this situation contributed to a lack of detailed technical information. At the same time, companies often compensate for this dearth of data by relying on storytelling to communicate about the properties and potential applications for their materials. As a result, both researchers and users seeking to understand these materials rely primarily on corporate marketing, trying to understand the characteristics of the materials that are, at this stage, often inaccessible in their physical form.

Given the importance of the concept of materials biography, both for the framing of the still undefined identity of novel materials and for understanding their main characteristics and sustainability performance, we further describe the five materials-biography categories previously mentioned to create new biographies for recent bio-based and bio-fabricated materials for the fashion industry.

Material-biography categories

As outlined above, we identify five material-biography categories to describe the nature and history of these innovative materials. At the moment, these categories do not fit with standardized approaches for presenting material information in products, particularly in terms of what is normally included on product labels. There is thus considerable potential to offer users additional relevant details to

Table 2. Material-biography categories.

Material-biography category	Material characteristics or quality highlighted from cases
Life cycle	Livingness, future cycles, end of life
Temporality	Growth rate, durability/degradation
Origin	Crop-based, biomass or waste-based, a biotech-based (organism)
Process	Techniques utilized, social and environmental impact
Identity	Completely novel, mimicking/substitute

support the current information provided in clothing labels (such as care instructions). This type of passport could be a way to improve transparency and to provide further material clarification of aspects that are still unknown, for example in terms of durability. The regulation of these categories could help producers, designers, and users to understand and care more effectively for these materials. There is ample room for furthering the design research around these first five categories (summed up in Table 2 and explained in further detail in the following section) and the concept of materials biography. Such investigations create opportunities to reflect on how we could communicate differently around conventional materials, including the new bio-based ones. Therefore, the categories provide a framework to rethink how to present the qualities and potentialities of materials.

Life Cycle

As outlined earlier, understanding the life cycle of products and materials is a fundamental aspect of a designer's environmental awareness. We have highlighted in this article how the life cycle becomes a key point of company strategies in the current discourse around biomaterials for fashion.

In a circular economy, the possibility and desirability of engaging with transparency and traceability as well as provenance and design has enabled materials to regain space and become foregrounded in experiences of users. As a material-biography category, these notions can inform the user on the state of the material (inert or still living) and on fundamental aspects that should be considered for its application in sustainable projects, for instance its renewability and end-of-life disposability.

Temporality

Notions about the growth rate and durability of materials are emphasized in the communications of our case studies. In other classes of materials, temporality begins when the material is applied to a product. Instead, in the cases of bio-based and bio-fabricated materials, temporality is considered from the beginning of a product's life cycle (i.e., when

conceived and developed). We observed through the cases that this category is frequently mentioned in the narratives around materials, although it is still abstract to the general public, especially given the novelty of these materials.

Origin

Origin is the most relevant element in the material narratives of the cases. In the textiles area, the practice of grouping and categorizing materials is common so it is not unusual to have “origin” named as a material category. Although this is a customary practice, it tends to be overplayed in the narratives. Whether a material is crop-based, biomass, waste-based, or biotechnology-based (organism), its origin becomes a critical starting point for bringing users into the stories of the materials. The link to places of origin proved so strong in our cases that it was often difficult to distinguish between the name of the company and the name of the material, which is usually a derivative from the material-source name. Some examples are materials that come from mycelium, the majority having names starting with “My” (as MycoTEX or Mylo), or similarly all the plant-based materials are directly related to the source (as seen in Piñatex or Bananatex).⁴³ In fact, a recent study on the communication of bio-fabricated materials pointed out the different wording and imagery that companies use to create the sense of the “original habitat” where the organisms come from and some of the processes that enable their transformation into usable material (D’Oliveo and Karana 2021). In fact, these are instructive insights in helping people imagine these organisms and processes that are still mostly unknown or unfamiliar to them.

Process

By “process” we mean the technologies and practices with which materials are developed, worked, and transformed. In this context, processes are not only applying the material to a product but also, and above all, concern the experimentation and development of the material itself. There are different ways where the understanding of processes appears relevant to our cases. First, the notion of process is apparent in references to how these materials are derived from a collaborative process between nature, humans, and technology. They are generally created with a specific function and certain sustainability criteria in mind. Second, the cases emphasize, an issue that we discussed above, that the boundaries between material production and application are blurred, with designers starting to interact with the making of the materials. These modes of

experimenting and tinkering make the creation and development processes of these materials more visible. As the socio-environmental impacts of the fashion industry become more compelling, this feature, besides facilitating transparency, will create more opportunities for users to understand and potentially be involved in these processes. Finally, users rarely experience these materials in the initial instance in their physical form. Rather, the first points of contact are virtual—via images, recipes, stories—and mediated in the digital environment. This is because these materials are not yet widely available in samples or product applications. Accordingly, the communication around processes helps build a relationship between users and these materials, creates the space for them to enter people’s lives, and forges the contexts for their experience.

Identity

The lack of physical experience presents yet another challenge for bio-based and bio-fabricated materials in the fashion sector concerning identity (Rognoli et al. 2011), namely what they are and their perceived and experiential qualities. Being unfamiliar to most people, many of these materials are often commercially introduced as substitutes for current less sustainable materials. Mimicking the properties of existing materials, but with added functionality and sustainability-related qualities, is a common objective in many of the cases that we observed. This insight emerged above and is described in Table 1. In a smaller number of cases, we noticed that materials are introduced as unique and innovative, presenting opportunities for innovative applications and encouraging practices to emerge around them. An important consideration is how to balance phasing out less sustainable materials and enabling new practices to emerge with these bio-based materials and their unique qualities. For the latter, it is crucial to encourage and nurture tinkering practices and experimentation with materials to reveal their unique potential (Rognoli and Parisi 2021; Barati and Karana 2019; Parisi et al. 2017).

Discussion

To facilitate and speed up the development and adoption of bio-based and bio-fabricated materials in the field of fashion (and perhaps also in other fields), it is necessary to disseminate the associated knowledge to the public, companies, and designers. With respect to designers who want to experiment with these materials and adopt a DIY approach (including tinkering with the materials and then

developing meaningful material experiences), they must intimately know the history of these materials and understand the salient features of their composition. This article has sought to establish a foundation for constructing a repository that emphasizes information related to the biography of these materials and to demonstrate how their unique characteristics differ from traditional alternatives in accordance with material-biography categories.

Given the environmental problems that derive from the fashion sector, it is mandatory to consider new material solutions. Talking about bio-based and bio-fabricated materials is essential. These materials are inspiring a new generation of designers and many of them have emerged by developing experimental practices. However, while the expectation is that new biomaterials will enhance sustainability performance, there is a lack of research that is independent from the manufacturing companies to assess their impacts, especially at scale. As noted above, there is currently a lack of transparency concerning the technical aspects of these materials due to concerns about protecting the intellectual property around the production technologies. We are hopeful that as they enter the market and become more accessible, additional information will be made available to both academic and industrial audiences. From a social standpoint, especially in the case of plant-based materials derived from cellulose extraction, it is important to recognize that reproducing old extractivist models solely focused on supplies of raw materials, as currently takes place in countries of the global South, may not be a sustainable solution despite the ostensibly desirable features of the resultant material. Sustainability efforts would also benefit from further studies measuring the impact of scaled production, gathering data not only on the environmental effects of particular materials, but also their social impacts, especially with respect to the consequences for local artisan and textile communities that have traditionally worked with the same fibers.

Recent experiences concerning bio-based and bio-fabricated materials are biased by the fact that the objective is for many of them to replace other existing counterparts and to mirror many of their qualities. While we recognize the importance of this intentionality to produce alternatives to either animal leather or oil-based fabrics, this focus overlooks the potentials of many of these new materials that are unique or inherent to each organism (Barati and Karana 2019) including liveliness, affectability, and responsiveness. These characteristics are likely to be much more extensively explored and articulated by independent designers and artists who, through their practice, are apt to develop a closer relationship with the materials. Our examination of the communication copy from the established

companies with trademarked materials prompts us to conclude that their apparent strategy is to appeal to the nostalgia of consumers based on their familiarity with customary materials (the ones they are trying to mimic) and to use this feature as the basis for establishing trust (“this will feel like real leather or rubber”) rather than describing the characteristics of the material itself. When companies present the new material, the focus is on storytelling, creating a narrative around the sustainable intentions of developing the technology, using technical descriptors and imagery such as laboratory equipment.

Future research on bio-fabricated materials could take a similar approach that focuses on their experiential qualities and moves beyond initial material-mimicking intentions. We argue that nourishing and supporting artistic sensibilities and DIY approaches is fundamental in allowing these material developments to flourish. Additionally, many regenerated or synthetic fibers were developed to imitate natural fibers and the implications of overlooking their unique material properties and potential impacts have been extremely unfortunate.

This study suggests that a greater understanding of these communication and marketing strategies could assist both users and other stakeholders to further explore the innovative potentials of these materials, hasten their transition to the market, and reduce the environmental burden of the fashion industry. Materials biography-based tools such as the materials-identity card could become helpful instruments to compare case studies and to promote newly developed products. At the same time, we are confident that these categories can be expanded and recognize the need to gather more data about the social and environmental impacts of these new materials.

Conclusion

This article has focused on building a panorama of possible alternative bio-based and bio-fabricated materials to support a lasting and effective transition toward more sustainable fashion. It has provided a comprehensive analysis of the most pressing socio-environmental challenges facing the industry and offered a comprehensive picture of the current actions being undertaken by governments, industry, and designers to transition to more sustainable practices. We also summarized previous literature on how the concept of the materials experience and the DIY Materials approach could positively contribute to the proliferation of alternative and sustainable materials with particular attention devoted to applications pertaining to fashion design.

We furthermore presented 24 cases of bio-based and bio-fabricated materials, grouped according to

their origin and provided details on both the origin and potentials of these emerging materials. The aim here was to raise awareness of the benefits of societal acceptance and to support the design community with new tools to understand and apply these novel materials in the fashion industry to achieve more sustainable results. We also introduced the concept of materials biographies to highlight categories that can be explored by designers, companies, and end-users in introducing these materials. The analysis of cases was fundamental for building the materials-biography categories which can facilitate understanding of the prominent narratives of these new materials, communicating their characteristics and fundamental life traits, namely, life cycle, temporality, origin, process, and identity. These material-biography categories were elaborated by drawing on the circular economy concepts of a material passport and a product biography which emphasize the need for tools to enhance the communication and traceability of such innovative materials.

Notes

1. See <https://www.greenpeace.org/international/act/detox>
2. Sustainable Fashion Summit, ECOSOC Chamber, Friday, 1 February 2019, H. E. Ambassador Inga Rhonda King, President of the United Nations Economic and Social Council. See <http://www.un.org/ecosoc/sites/www.un.org.ecosoc/files/files/en/president/2019/remarks-ecosoc-president-sustainable-fashion-summit-01-feb-2019.pdf>
3. It has been estimated that around half a million tons of microfiber, which is the equivalent of 3 million barrels of oil, is now being dumped into the oceans every year. See <https://news.un.org/en/story/2019/03/1035161>.
4. See <https://unctad.org>.
5. See [https://www.europarl.europa.eu/RegData/etudes/ATAG/2020/656296/EPRS_ATA\(2020\)656296_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/ATAG/2020/656296/EPRS_ATA(2020)656296_EN.pdf)
6. See <https://bangladeshaccord.org>.
7. See <https://www.eea.europa.eu/publications/textiles-in-europes-circular-economy>.
8. See <https://www.circle-economy.com/news/our-world-is-now-only-8-6-circular>.
9. See <https://cfda.com/resources/sustainability-resources>.
10. See <https://apparelcoalition.org/higg-product-tools>.
11. See <https://www.greenstrategy.se/sustainable-fashion/seven-forms-of-sustainable-fashion>.
12. See <https://www.lvmh.com>.
13. See <https://taukodesign.com/pages/textile-recycling>
14. See <https://rapanuclothing.com>.
15. See <https://group.ferragamo.com/en/news/2017/orange+fiber>.
16. See <https://resortecs.com>.
17. See <https://fashionchecker.org>.
18. See <https://cleanclothes.org/fashions-problems>.
19. See <https://knownsupply.com>.
20. See <https://www.instagram.com/marchenoirlomeparis/?hl=it>.
21. See <https://www.re-pearls.com/post/a-day-in-the-life-of-a-textile-designer>.
22. See <https://www.modernmeadow.com>.
23. The Materials Driven Design (MDD) method supports design for meaningful material applications with the material as a point of departure. Designers quality the materials not only for what they are, but also for what they do, what they elicit from us, what they express to us, and what they make us do. The process comprises four main action steps, starts with a material (or a material proposal), and ends with a product and/or further development of materials. See <http://materialexperiencelab.com/material-driven-design-method-mdd>.
24. The DIY movement is expanding beyond artifacts to include the materials from which products are made, namely DIY-Materials. DIY-Materials are created through individual or collective self-production experiences, often by techniques and processes of the designer's own invention, as a result of a process of tinkering with materials. They can be new materials with creative use or other substances as material ingredients, or they can be modified or further developed versions of existing materials. Designers from all over the world are engaged in various experimental journeys in the field of material development, and they consider these experiments as the starting point of their design process which will lead to the creation of new artifacts. The possibility to self-produce their own materials provides designers with a unique tool to combine unusual languages and innovative design solutions with authentic and meaningful materials experiences.
25. See <https://www.vegeacompany.com/> and <https://orangefiber.it/it>.
26. See <https://www.ecovative.com>, <https://mogu.bio>, <https://www.mycoworks.com>, and <https://www.modernmeadow.com>.
27. See <http://www.newstatesman.com/spotlight/emerging-technologies/2020/07/biomanufacturing-path-sustainable-economic-recovery>.
28. See <https://malai.eco>.
29. See <https://www.pili.bio>, <https://colorifix.com>, and <https://www.ginkgobioworks.com>.
30. See <https://boltthreads.com/technology/microsilk>.
31. See <https://www.zoamaterials.com/zi>.
32. See <https://www.algiknit.com>.
33. See <https://www.vollebak.com/product/plant-and-algae-t-shirt>.
34. See <https://www.dezeen.com/2014/10/14/blond-and-bieber-algaemy-coloured-dye-algae-lodz-design-festival-2014>.
35. See <https://ecovatedesign.com/mycoflex>.
36. See <https://www.kickstarter.com/projects/boltprojects/the-mylo-driver-bag>.
37. See <https://www.mylo-unleather.com>, <https://www.adidas.co.uk/blog/663481-stan-smith-mylo-tm-made-using-mushrooms>, <https://www.mylo-unleather.com/stories/stella-mccartney-debuts-a-mylo-bustier-top-and-trouser-set/>
38. See <http://pura.mogu.bio/project/pural-materials>.
39. See <https://www.ananas-anam.com>.
40. See <https://www.allbirds.co.uk/pages/our-materials-sugar>.
41. See <https://www.braskem.com.br>.
42. See https://ec.europa.eu/environment/publications/proposal-ecodesign-sustainable-products-regulation_en.

43. See https://ec.europa.eu/environment/publications/proposal-ecodesign-sustainable-products-regulation_en.

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