ANALYZING SUSTAINABILITY IN FASHION THROUGH BIO-SYNTHETIC MATERIALS

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Abstract

The environmental consequences of the fashion industry are undeniably severe and contribute to environmental pollution and degradation in many ways. While sustainability discussions are continuing, new material trends are emerging and the source, production process, and experience of these materials also affect the fashion industry. Synthetic biology is a promising tool combining bio-design and bioengineering. This new bio-synthetic approach offers an innovative path toward ethical and clean fashion production by transforming microbes or bacteria into "living factories" that produce sustainable materials. However, a broader evaluation is required to grasp the full potential and ethical challenges, especially regarding the commodification of living organisms for mass production. It is imperative that research be conducted to assess the environmental, social, and economic impacts of bio-synthetic materials, particularly in the context of the "living factories" concept. Considering the ethical risks of exploitative practices and the need for transparency, this study examines bio-synthetic applications in fashion, their impacts on sustainability, and their implications for planetary well-being.

Keywords: *Sustainability in fashion, Planetary well-being, Bio-synthetic materials, Living factories, Ethical practices*

INTRODUCTION

The environmental consequences of the fashion industry are extremely severe, straining the planet and contributing to environmental pollution and degradation. The extensive supply chain in the fashion industry has many negative impacts such as water and energy use, chemicals, water and air pollution, microplastics, and waste. Such impacts push the planet to its limits, harm its well-being, and adversely affect human well-being both socially and economically (Jacometti, 2019).

The pressing necessity to confront the environmental and social consequences of the fashion industry underlines the potential of prosperity fashion to establish a regenerative approach. This concept advocates a model that respects ecological limits and emphasizes responsible production, prioritizing the well-being of the planet and societies over profit (Badhoutiya et. al., 2023).

Integrating technology into biology plays a crucial role in contributing significantly to the well-being of the planet by creating new opportunities for sustainable fashion, increasing productivity, and reducing waste. Synthetic biology facilitates the enhancement and regulation of characteristics and functions within complex cellular matrices by developing standardized frameworks that enable the production of desired materials (Gallup et. al., 2021).

In contrast to conventional synthetic processes that rely on petrochemicals and energy-intensive methods, bio-synthetic materials can be produced controlled, and resource-efficient. However, unlike traditional design materials, biological entities have their intrinsic properties and responses, making prediction and standardization difficult in practice (Frow & Calvert, 2013; O'Malley, 2009), and also raising complex ethical concerns regarding the commodification of living organisms and the need for transparency to maintain ethical standards in production.

The emergence of bio-synthetic materials signifies a potential transition towards a more sustainable and ethical fashion industry. However, without critical reflection, these innovations may perpetuate the exploitative practices that the concept of sustainability seeks to address. This represents a gap in both the literature and discussions surrounding their applications.

This study aims to examine the current status of bio-synthetic materials to advance a more sustainable and ethical fashion industry. In particular, the study objectives include (1) exploring the bio-synthetic materials and the concept of *living factories* in fashion, and its impact on sustainability; (2) analyzing the ethical considerations around commodifying living organisms, particularly when scaled for mass production.

LITERATURE REVIEW

There is a significant negative impact of the fashion industry on ecosystems and human societies in terms of greenhouse gas emissions, pesticides, microplastics released from synthetic fabrics such as polyester, exploitation of fresh water, air pollution, and disruption of the environment (Hibberd, 2019). The linear production model adopted by fast fashion points to systematic problems in the industry and highlights the necessity for the implementation of more sustainable practices that prioritize resource efficiency and waste reduction (Chen et al., 2021). For the fashion industry to meet the requisite climate targets, a reduction in resource use of between 75% and 95% from current levels is necessary (Sharpe et al., 2022). The fast fashion industry places a significant burden on the environment through the extraction of vast quantities of resources to manufacture garments (Ellen MacArthur Foundation, 2017; ETC/CE Report, 2023/5). Global fiber production has increased exponentially over the past two decades, reaching 58 million tonnes in 2000, and is projected to reach 147 million tonnes by 2030 (Textile Exchange, 2023). The majority of these fibers are synthetic, comprising 63% of the total (Ellen MacArthur Foundation, 2017). The increased and unsustainable production and use of materials have stimulated the growing demand for more responsible alternatives in the fashion industry. This has led to the development of new materials and the re-evaluation of existing ones (McNeill & Venter, 2019).

The production of fibers for use in the manufacture of garments represents the primary source of environmental damage within the supply chain (Moazzem et. al., 2022). Plant-based fibers, including organic cotton, bamboo, hemp, jute, and ramie, and animal-based fibers and materials, such as wool are increasingly being acknowledged as environmentally friendly alternatives in sustainable textiles. Although natural fibers have typically been regarded as sustainable in the context of fashion, the advent of heavy industrialization has introduced a degree of uncertainty regarding the sustainability of natural materials (La Rosa & Grammatikos, 2019; Zhao et al., 2021).

Synthetic biology is emerging as a promising solution in this context, as defined by the European Commission in a 2005 report "*Synthetic biology is the engineering of biology: the synthesis of complex, biologically based (or inspired) systems that display functions not found in nature*" (European Commission, 2005). In alignment with this view, Calvert (2010) suggests that synthetic biology offers an alternative means of production through the transformation of biological organisms that produce materials, which includes the construction of completely novel biological entities, and the re-design of already existing ones. This innovative approach not only employs the potential of biological systems to address environmental challenges but also enables the creation of high-performance materials that align with sustainability goals. Bio-synthetic materials are derived from a bio-based, renewable source and are employed as replacements for traditional synthetic materials due to their performance and technical properties (Textile Exchange, 2022). Nevertheless, they are synthesized or engineered with the intention of replicating the properties of synthetic polymers or other materials with specific functional characteristics (Collet, 2018). In contrast to conventional techniques, bio-synthetic materials have the potential to significantly reduce water and land usage, as well as minimize carbon emissions, through the utilization of renewable biological resources (Redford et al., 2019).

The fashion industry is increasingly adopting bio-synthetic materials as a sustainable alternative to traditional textiles. To gain a deeper comprehension of the extent and future possibilities of these materials, it is essential to first establish a clear understanding of the conceptual framework surrounding the term 'bio' and its associated contexts.

Figure 01 categorizes bio-synthetics as a subset of biomaterials, highlighting their origin from biological systems and their engineered properties designed to replicate or improve upon conventional materials. Bio-synthetics are further subdivided based on production methods, such as fermentation, microbial synthesis, or bioengineering of renewable biomass (Biofabricate and Fashion for Good, 2020). Within this framework, "living factories" are defined as the use of living organisms such as bacteria, fungi, algae, or yeast as bio-fabricators of materials. In Figure 1, the intersection between bio-fabrication and bio-synthetics is highlighted in green to emphasize their convergence within the conceptual framework.

Fish (2013) discusses the concept of "living factories" as a means of utilizing biological processes as a source of production. In contrast to conventional organisms, transgenic beings are engineered to perform tasks that they would not naturally undertake, thus positioning them as self-acting machines that transform raw materials into valuable products. Originating in the fields of pharmaceuticals and food, these developments have progressed to the re-engineering of yeast, bacteria, and other cells to produce plastics, biofuels, and textiles, resulting in the creation of living factories that are more cost-effective, straightforward, and environmentally friendly than traditional industrial methods (Eisenstein, 2016). The concept of living factories is in line with Callot's (2021) framework for designing with living which includes "nature as a co-worker" and "nature as a hackable system". Working with organisms to develop materials, designers adopt a collaborative approach in practice, embracing the concept of 'living factories' that function as production units. Moreover, by modifying or reprogramming organisms, they are now capable of functioning as "factories" adapted to produce specific outputs without depleting ecosystems (Callot, 2021). Production methods of bio-synthetic materials vary with the focus of living factories including utilizing bacterial fermentation, plant extraction, chemical synthesis, and controlled cultivation of fungal structures, each offering distinct benefits and challenges (Daukantienė, 2022; Saha et al., 2020). An increasing number of major textile and fashion brands are incorporating bio-synthetic materials into their sustainability initiatives, offering environmentally friendly alternatives to conventional synthetic and natural materials. Adidas, Stella McCartney, Nike, Balenciaga, and The North Face are among the leading brands investing in this technology. However, critical environmental considerations include the consumption of resources, the emission of greenhouse gasses during the production process, and the biodegradability of the end products. To fully realize the potential of bio-synthetic materials, it is essential to address several challenges, including scalability, cost competitiveness, material performance, consumer acceptance, and ethical considerations.

METHODOLOGY

This study employs a qualitative review and analysis to examine recent developments in bio-synthetic material applications within the fashion industry, with a particular focus on the interpretation of living factories. To evaluate the application of bio-synthetic materials in the fashion industry, six initiatives and their applications were selected and analyzed in terms of functionality, sustainability, and scalability. Emerging patterns and gaps in the literature and practice were discussed, particularly regarding the environmental, social, and ethical dimensions of these applications. A critical evaluation framework was applied to assess the ethical and social implications of biosynthetic materials, with particular attention to issues such as commodification and potential exploitation.

OVERVIEW OF BIO-SYNTHETIC MATERIAL APPLICATIONS IN FASHION

Currently, a range of materials in the fashion industry is being developed from a catalytic transformation of biomass or fermentation of living microbes, bacteria, or yeasts. Some examples included in this research for our analysis are: (1) Mylo by Bolt Threads another leather alternative that is crafted from mycelium, (2) Spiber Inc.'s Brewed Protein designed to replicate the properties of natural proteins like silk and keratin, (3) Modern

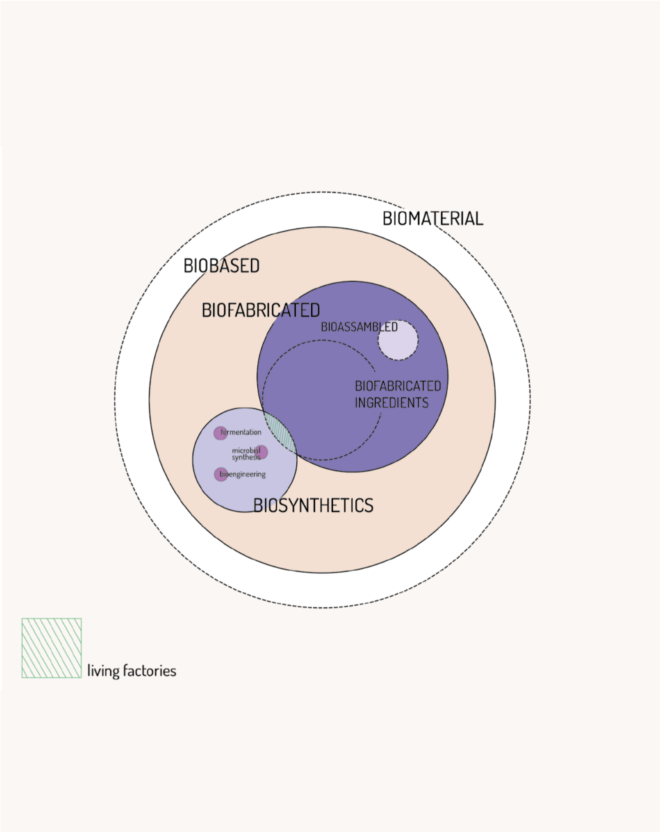

Fig. 01

Meadow's Bio-VERA a leather alternative powered by Bio-Alloy, a blend of plant-based proteins, (4) Modern Synthesis' Microbial Textiles created by harnessing sugar-eating bacteria to produce nanocellulose, (5) Oxman's O° which utilized PHA -bacterially produced thermoplastic polymers, (6) Pneuma's OXYA a living textile fiber embedded with microalgae and performs photosynthesis. The first three examples demonstrate higher technological maturity and scalability. They are already used in commercial applications and have collaborations with major textile and fashion brands. In contrast, the other examples are more recent research-focused projects.

Table 01 provides a summary of the key bio-synthetic material innovations by living factories concept, which will be analyzed in this section. The table presents their specific functionalities, sustainability attributes, and scalability potential.

(1) ***Mylo by Bolt Threads***, represents a significant advancement in the field of bio-synthetic materials, utilizing mycelium, the root-like structure of fungi, as a raw material. Mylo is composed of 85% mycelium derived from fungi and 15% lyocell, a regenerated cellulose fiber, and is finished with a water-based polyurethane (PU) coating that enhances its durability (Pariti et al., 2024). The process begins with the cultivation of the mycelium within a controlled environment. As the mycelium grows, it transforms into a dense and interconnected network of fibers, which serve as the base material. This phase is conducted with the aid of molds or trays, to ensure uniformity in dimensions and thickness, thereby reducing the quantity of material that is wasted. Once the mycelium mat has reached full growth, it is harvested and cleaned to remove any remaining substrate. It then undergoes environmentally friendly tanning and finishing processes (Vandelook et. al., 2021). The entire process is efficient, typically completed within weeks, and has a minimal environmental impact (D'Olivo & Karana, 2021). The combination of a rapid production cycle, chemical-free processing, and waste minimization positions Mylo as a novel bio-synthetic material (Jhanji, 2022). The scalability of Mylo is dependent upon two key factors: firstly, the efficient production process employed in its manufacture; and secondly, the sustainable resource inputs utilized (Baars et. al. 2024). The utilization of renewable agricultural by-products, including sawdust and corn stalks, as raw materials ensure a cost-effective and abundant supply of raw materials (Rathinamoorthy et. al., 2023). Furthermore, minimal water and energy requirements facilitate large-scale production, rendering it both economically and environmentally sustainable (Pariti et. al., 2024).

Collaborations with prominent brands such as Stella McCartney (i.e. bags), Adidas (i.e. Stan Smith sneakers), and Lululemon (i.e. yoga bags) have integrated Mylo into existing supply chains, thereby encouraging market adoption. (Yadav et. al., 2024). Nevertheless, challenges such as the current high cost of production in comparison to traditional leather require sustained investment in advanced bio-fabrication facilities, modular systems, and automation to enhance capacity and reduce costs (Nithyaprakash et. al., 2020).

Bolt Threads has encountered difficulties in continuing production of Mylo, a synthetic spider silk material, due to a combination of economic challenges, inflation, and a paucity of funding opportunities, despite having received $300 million in investments. While some major brands had adopted Mylo, the company experienced challenges in scaling up production on a commercial scale.

Categorization of bio-synthetic material examples

Example	Functionality	Sustainability	Scalability
Spiber Inc's Brewed Protein™	Durable, flexible, and strong protein polymers used in textiles, medical devices, aerospace; mechanical properties modifiable for specific applications.	Mitigates fossil fuel reliance, reduces greenhouse gas emissions, decomposes naturally, and prevents microplastic pollution.	High initial production costs; improvements needed in fermentation efficiency and feedstock diversification to compete with petrochemical materials.
Modern Meadow's Bio-VERA™	Durable, breathable, and flexible bio-synthetic material suitable for clothing and interior applications with customizable textures and colors.	Minimizes greenhouse gas emissions, water, and energy consumption; fully renewable Feedstock and solvent-free processes.	Ready for commercial production with capacity to produce 500,000+ square meters annually; supported by partnerships and collaborations.
Mylo™ by Bolt Threads	Flexible, durable bio-synthetic leather alternative from mycelium, incorporating advanced finishing for enhanced functionality.	Reduces water and energy use, avoids harmful chemicals, uses agricultural waste, and integrates waste-derived raw materials.	High production costs compared to traditional leather; requires investment in modular bio-fabrication systems and scaling automation.
Modern Synthesis' Microbial Textiles	Lightweight, strong microbial textiles grown directly into shapes using bacterial fermentation and robotic weaving techniques.	Fully biodegradable, eliminates textile waste through precise growing methods, integrates with circular economy models.	Resource-intensive fermentation processes limit scalability; requires engineering solutions and advanced bioreactors for higher efficiency.
Oxman's 0°	Single-material3D-printed biodegradable shoes tailored for diverse applications like athletics and ballet, using advanced robotic fabrication.	Uses renewable PHA-based materials, incorporates timed decomposition for environmental reintegration, reduces manufacturing waste.	Resource-intensive fermentation processes limit scalability; requires engineering solutions and advanced bioreactors for higher efficiency.
Pneuma's OXYA™	Photosynthesis-enabledtextiles that produce oxygen, sequester carbon dioxide, and actively enhance environmental health during use.	Captures and stores carbon dioxide, reduces greenhouse gases, promotes air quality, and utilizes microalgae in a biopolymer matrix.	Requires controlled conditions for photosynthesis; exploring partnerships with architectural firms for innovative applications.

Tab. 01

Consequently, the company has redirected its focus to its other flagship product, b-silk (Halliday, 2023).

(2) ***Spiber Inc.'s Brewed Protein*** represents an innovative bio-synthetic material obtained through microbial fermentation processes utilizing plant-based sugars as raw materials (Ferreira et. al., 2023). By employing genetically modified microorganisms, Spiber Inc. synthesizes protein polymers from plant-derived sugars that exhibit analogous characteristics to those of natural proteins, such as silk and keratin (D'Olivo & Karana, 2021). These polymers display remarkable tensile strength, flexibility, and biocompatibility, making them suitable for a diverse range of applications in textiles, medicine, and aerospace (Rouse & Van Dyke, 2010). To meet the requirements of a variety of potential applications, for instance, the mechanical properties of proteins (elasticity, durability, etc.) can be modified, thus facilitating their utilization in textiles, medical devices, or composite materials. A significant benefit of this biological approach is that it mitigates the reliance on fossil fuels and considerably reduces greenhouse gas emissions compared to conventional synthetic material production (Oh et. al., 2021). A life cycle analysis demonstrates that the manufacture of Brewed Protein results in significantly lower emissions of greenhouse gases than the production of nylon or polyester (Lips, 2021). Furthermore, its capacity to decompose naturally after its life cycle serves to minimize environmental degradation by preventing the pollution of microplastics that are associated with persistent synthetic polymers (Tachibana et al., 2021). The scaling up of production to compete with petrochemical counterparts remains a significant challenge, largely due to the high costs associated with initial production (Breslauer, 2024). However, innovations in fermentation efficiency and feedstock diversification have the potential to overcome these barriers. For example, important commercial collaborations such as The North Face's "The Earth Hoodie," a fleece made with Brewed Protein fiber, have demonstrated the potential for sustainable clothing (Chow, 2022). Furthermore, collections designed using Brewed Protein fiber were launched in 2023, including those from The North Face, Goldwin, Nanamica, and Woolrich (Goldwin, 2023).

(3) ***Modern Meadow's Bio-VERA*** is a bio-synthetic technology crafted using Modern Meadow's Bio-Alloy technology, a blend of plant-based proteins and bio-based polymers that mimics the functional properties of proteins, and by integrating this membrane technology with a fully renewable material derived from post-consumer car tire feedstock (Nutley, 2023). This material has a wide range of applications in the textile and fashion industries. Especially in the context of clothing, the material offers a sustainable alternative, exhibiting features such as high durability, breathability, and flexibility (Harrell, 2024).

Bio-VERA requires less greenhouse gas emissions, water, and energy consumption than traditional leather and synthetic materials. It is anticipated that Bio-VERA will become a more widely used material in the future, with new textures and color options, integration with smart textiles and wearable technologies, and the creation of sustainable innovations in fashion and other industries (Modern Meadow, 2023). Modern Meadow has recently announced that it is prepared to commence commercial production of Bio-VERA and can produce over 500,000 square meters of Bio-VERA per annum (Bringle, 2024). Additionally, in a press release, Modern Meadow announced its collaboration with Earthletica, a green-tech activewear brand, to create the Bronte Jacket, named in honor of swimmer Bronte Campbell OAM (PR Newswire, 2024).

(4) ***Modern Synthesis' Microbial Textiles*** can be compared to the traditional practice of weaving, involving the growth of bacteria-based material around a pre-designed "warp" structure. This structure is crafted using robotic yarn or fiber placement. The bacteria effectively form the "weft", producing a strong and lightweight bio-synthetic material that eliminates waste by enabling pieces to be grown to precise shapes, much like 3D printing (Textile Technology, 2022). The process draws inspiration from the natural behavior of K. rhaeticus, a bacterium renowned for its capacity to produce nanocellulose (Raru et. al., 2023). These fibers form a dense, interconnected network that can be directly shaped during production by controlling the parameters of the fermentation process, including the composition of nutrients, temperature, pH, and oxygen availability (Madhu & Chakraborty, 2017). This enables the creation of tailored textile properties, including thickness, texture, and flexibility, without the necessity for post-processing steps that are typically required in conventional textile production (Girard et. al., 2024). The production process is distinctive in that it eliminates the necessity to spin fiber from raw

materials as well as for cutting and sewing excess material, which is a common source of textile waste (Morgan, 2023). As fully biodegradable materials, microbial textiles naturally decompose at the end of their life cycle, thereby integrating seamlessly into circular economy models and avoiding the microplastic pollution associated with synthetic fibers (Nayak et al., 2024).

Despite the sustainability advantages of microbial textiles, scaling up production to meet global textile demand presents a significant challenge, given that the fermentation processes involved are slower and more resource-intensive than conventional methods (Katyal et. al., 2023). Therefore, Modern Synthesis is investigating methods to enhance the scalability of this process. Strategies include the engineering of bacterial strains to facilitate accelerated growth or achieve elevated yields, the design of more efficient bioreactors for large-scale production, and the utilization of cost-effective feedstocks such as agricultural waste (Modern Synthesis, n.d.). Although the company's most well-known product is the prototype sneaker, called 'This is Grown', produced by Jen Keane, the founder of Modern Synthesis, in 2018, the company is continuing its commercialization efforts with $4.1 million in funding by 2022 (Marston, 2022).

(5) ***Oxman's O°*** integrates the disciplines of material science, architecture, and biology to develop a system whereby materials and structures are produced through biological processes rather than manufactured (Harrell, 2024). O° is founded on the principles of Material Ecology, a design philosophy coined by Neri Oxman that incorporates natural processes into the creation of materials and structures (Oxman, 2020). A fundamental aspect of O° is growth-based manufacturing, which entails the utilization of biological techniques such as microbial growth and mycelium cultivation for the generation of materials, as opposed to the conventional reliance on industrial synthesis (Saunders, 2024). The material is derived from polyhydroxyalkanoates (PHAs), an organic, bacterially sourced thermoplastic material that has been identified as a sustainable alternative to petroleum-based plastics. The PHA-based material is combined with cutting-edge manufacturing techniques, including hot melt spinning, 3D knitting, and 3D printing (Boissonneault, 2024).

As an example of a product, O° shoes are crafted from a single biomaterial, in contrast to traditional footwear, which is composed of over 40 distinct materials and processes, including cutting, sewing, and gluing (Oxman, n.d.). The construction of each shoe entails the creation of a fundamental base layer, which is crafted from PHA fibers and knitted into a flexible sock-like structure (Oxman, n.d.). Moreover, the characteristics of the material can be modified during the manufacturing process to suit a range of applications, including footwear for athletic activities and ballet slippers (Chen, 2024). The natural biodegradability of PHAs in marine and soil environments prompted Oxman to incorporate timed degradation characteristics into O°. This approach, which may be described as "programmed decomposition," encourages users to consider carbon sources and environmental processes, including the requisite time, location, and conditions for the material to return to the ecosystem (Saunders, 2024). The utilization of renewable raw materials facilitates the implementation of scalable, localized production processes with a carbon-neutral or carbon-negative footprint. Notwithstanding the persisting challenges associated with scalability costs and PHA production optimization, the material's unified approach and the growing consumer demand for sustainable products position it on the path to commercialization.

(6) ***Pneuma's OXYA***, a bio-synthetic material that represents another approach that incorporates photosynthesis into textiles. The integration of microalgae into textiles enables the OXYA material to consume carbon dioxide and release oxygen, thereby transforming garments and household items into living systems that contribute to environmental health (IndieBio, n.d.). The OXYA process involves the integration of a diverse range of microorganisms, including algae, fungi, and bacteria. The microorganisms are selected for their capacity to convert sunlight and carbon dioxide into oxygen and biomass, thereby actively sequestering atmospheric carbon into stable forms that contribute to long-term storage. Furthermore, they enhance the material's capacity to capture carbon throughout its active lifespan by increasing its biomass (In-na, 2022). The biopolymer matrix is designed to provide the necessary support for the metabolic activity of these microorganisms, enabling them to survive for up to six months under controlled conditions while maintaining efficient photosynthetic and carbon capture performance (Ayyanar et. al., 2023). The optimiza-

tion of light exposure and nutrient supply enables the microorganisms within OXYA to engage in maximal photosynthesis, thereby facilitating the improvement of air quality and the reduction of greenhouse gasses. This approach is intended to provide both immediate and ongoing environmental benefits.

In its initial collaboration with a prominent New York-based architectural firm renowned for its signature projects, including the High Line and MoMA, Pneuma seeks to develop pioneering applications, particularly in the domain of interior textiles with OXYA (Newsfile Corp., 2024).

DISCUSSION

The implementation of bio-synthetic materials in the fashion industry offers a transformative opportunity to address the environmental and social challenges associated with traditional textile production. Nevertheless, it is imperative to subject these technologies to rigorous examination concerning their scalability, transparency, and ethical implications. One of the principal advantages of bio-synthetic materials is their capacity to supplant resource-intensive and environmentally deleterious processes with more sustainable alternatives. Materials such as Spiber's Brewed Protein, Modern Meadow's Bio-VERA, and Bolt Threads' Mylo exemplify the versatility and innovation within this field. The production of these products involves processes such as microbial fermentation and fungal cultivation, which not only result in a reduction of greenhouse gas emissions but also contribute to the minimization of waste through the incorporation of renewable feedstocks. Furthermore, the capacity of bio-synthetics to decompose naturally addresses the urgent issue of microplastic pollution associated with conventional synthetic textiles. Nevertheless, the extent to which these materials can replace traditional materials depends on their ability to be produced on a larger scale while maintaining affordability and reducing their environmental impact.

Notwithstanding the promise of these innovations, significant gaps in transparency present an obstacle to a comprehensive evaluation of their true sustainability. It is imperative that these processes are transparent to establish credibility and ensure that claims of sustainability are substantiated. For instance, this study encountered limited accessibility to detailed information regarding the production protocols, resource inputs, and waste management strategies associated with Modern Meadow's Bio-VERA and Pneuma's OXYA. Moreover, although bio-synthetics are typically promoted as environmentally friendly, comprehensive life cycle assessments are essential to evaluate their environmental benefits in comparison to conventional materials such as polyester or leather. In the lack of such data, there is a risk of perpetuating an unsustainable system under the guise of innovation.

The ethical considerations are of equal importance in the discussion of bio-synthetic materials. The utilization of genetically modified organisms in textile production raises concerns regarding the commodification of living systems, particularly when scaled up for mass production. Although technologies such as living factories, which utilize organisms such as bacteria, fungi, and algae as material producers, are commended for their innovative approach, they also serve to merge the distinctions between the natural and industrial realms. Such commodification risks reducing living organisms to mere tools of production, which may in turn encourage exploitative practices. Furthermore, uncertainty persists regarding the long-term sustainability of engineered organisms within production systems. Key considerations include the methods of maintenance, control, and disposal at the end of their life cycle.

The scalability of these technologies is also a challenge. While some materials, such as Spiber's Brewed Protein, show potential for large-scale production, others, such as Modern Synthesis' Microbial Textiles and Oxman's O°, remain experimental or niche due to limitations in cost efficiency and production speed. Investments in advanced bio-fabrication facilities, raw material optimization, and automation will be crucial to overcome these barriers.

CONCLUSIONS

The technologies of bio-synthetic materials investigated in this research are related to living factories, employing biological processes to address critical environmental concerns, including carbon emissions, water pollution, reliance on fossil fuels, and microplastic waste. This research highlights some studies and examples of bio-synthetic materials that have been developed as fashion products.

Although interest in these new materials is steadily growing, the market for them remains predominantly niche at this stage. To drive broader adoption, further research is essential, including rigorous assessments to demonstrate that these novel processes and materials indeed have a lower environmental impact compared to existing alternatives. Equally important are studies addressing the challenges of scaling these technologies including economic feasibility.

From a political and systemic perspective, critical questions also arise. One of the most pressing is whether these innovations will genuinely contribute to a sustainable transformation or merely reinforce the unsustainable practices of the current system. Addressing these uncertainties requires a holistic approach that integrates environmental science, policy-making, and systemic change to ensure that these technologies align with broader sustainability goals.

Further work is required to overcome these challenges and facilitate the transformation necessary to establish a fully sustainable and ethical fashion industry. Systematic research is essential to evaluate the environmental, social, and economic impacts of bio-synthetic materials, especially within the framework of the "living factories" concept.

CAPTIONS

[Fig. 01] Classification of bio-synthetics (Adapted from Biofabricate and Fashion for Good, 2020, p.6) and positioning of living factories.

[Tab. 01] Categorization of bio-synthetic material examples.

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