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Fashion's Future: The Power of Biomaterials and Digital Manufacturing for Systemic Sustainability

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Abstract
In an era where fashion mirrors the excesses of a society driven by disposability, the garment emerges as a profound site for reimagining our relationship with identity, technology, and the environment. This paper explores the transformative potential of biomaterials and digital manufacturing in redefining fashion as a sustainable and ethical practice. Situated within the post-Anthropocene discourse, it examines its environmental and social impacts drawing on theoretical frameworks and on the analysis of punctual cases study that investigates the intersection of biomaterials and 3D printing. The paper critically addresses the existing barriers which hinder widespread adoption advocating for a systemic model that integrates innovation, ethics, and environmental consciousness.

Keywords: Biomaterials; Digital fabrication; Systemic fashion; Self-Growing materials; Entangled ecosystems.

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Introduction

From its beginnings, fashion has been a reflection of the human condition, embodying the need for expression, belonging, and identity. In the era of advanced capitalism, it has lost much of its cultural and craft dimension, becoming a symbol of overproduction and waste instead. In his analysis of consumer society, Baudrillard (1970) defines fashion as a self-referential system based on an infinite circle of production and obsolescence, dramatically contributing to environmental degradation and social exploitation. In the context of the post-Anthropocene era, Morton's (2013) philosophical concept of hyperobject appears particularly adequate to frame a contemporary understanding of what fashion is today: a complex, widespread, and interconnected system. As a hyperobject, fashion has consequences that transcend the here and now, affecting the entire terrestrial ecosystem and making it necessary to critically question its role as a tool for ecological, social, and cultural transformation. The effects caused by fashion on our ecosystems are now well-known, and these data are well-established: the fashion industry contributes, in fact, to 10% of global carbon emissions and 20% of water pollution (McKinsey, 2020), making it one of the most urgent industrial sectors where to act. The research on new materials and manufacturing techniques offers unprecedented opportunities to address this crisis; the one evaluated in this contribution relates to this intersection and the potential of biomaterials to redefine the very concept of fashion, mitigate damages, and actively contribute to ecosystem regeneration (3D Printing Industry, 2022).

Contemporary fashion reflects a system of overproduction fueled by an economic model that prioritizes immediate profit over sustainability. The fast fashion culture embodies what Guy Debord (1967) calls "society of the spectacle", where the production of ephemeral goods and the image take on a greater value than the intrinsic one. This approach is a manifestation of extractive capitalism, which treats nature as an infinite resource and waste as an external issue (Moore, 2015). The urgency of redefining such an unsustainable system involved many fields of competence; among them, biologists took significant traction, giving rise to a rapidly evolving field of Biodesign. This area of design utilizes living materials, such as cultured tissues and plants, embodying the vision of organic design by allowing nature to shape objects after an initial human intervention. When living organisms replace conventional materials like plastics or wood, the implications extend far beyond aesthetics or functionality, challenging traditional notions of comfort and progress. This shift pushes design into the moral realm, provoking reflection on deeply ingrained beliefs and ethical considerations (Myers, 2019).

This contribution aims to position itself at the jointure of these collaborative areas of experimentation with the purpose of critically analyzing the role of biobased fashion in contemporary society, exploring the potential of a systemic approach, with the objective of critically evaluate how biomaterials can transform fashion from a symbol of unbridled consumption to a resilient and harmonious model (Papanek, 1985).

Rethinking Sustainability Beyond the Anthropocene

In response to the current state of affairs, numerous critical movements have come into being: Kate Fletcher (2014) points out that fashion, as a cultural and industrial phenomenon, has the potential to drive systemic change, introducing the now well-known concept of "slow fashion" which favours quality over quantity (Gwilt, 2014). From this perspective, some limitations of distributed additive manufacturing and biomaterials, linked to slower times, can lead to a meeting point. This approach

encourages a more conscious and sustainable relationship between producer, consumer and environment: "Fashion is not just about what we wear, but about how we relate to the world" (Fletcher, 2014, p.45).
In line with this movement, designers wield significant power by crafting scenarios and prototypes that influence behaviour. Michel Serres (1990), in his work *Le contrat naturel*, calls for a "natural contract" between humanity and the planet, recognizing the need for an ethical balance between production and sustainability, recognizing the deep relationships between human and natural ecosystems, which are and should not be, longer distinguishable. Indeed, as Parisi (2021) argued, biomaterials disrupt the linear narrative of production and waste, suggesting a cyclical temporality that aligns with ecological interdependence rather than industrial determinism. This marks a departure from the Cartesian separation of nature and culture, reimagining fashion as a human endeavour and a collaborative act with non-human agents.
In this perspective, the use of materials like mycelium, algae, and bio-engineered tissues can represent a significant step towards this entangled vision; research on biomaterials is garnering increasing attention indeed, foregrounding the exploitation of renewable resources, promising a biodegradable and ethically aligned alternative to plastics and animal leather.

The impact of biomaterials
Many conventional textiles depend on plant materials or petrochemicals, innovative projects like BioCouture (2013), one of the first to give birth to actual products, explore how microorganisms can grow biomaterials for use in fashion and beyond [Fig.01]. Through the fermentation of sugar, bacteria spin cellulose microfibrils, forming a flexible and compostable material that can be shaped or sewn like traditional textiles (Lee, 2013).
Despite the disruptive meaning of this project, these materials still need to be enhanced in durability, water resistance, and biodegradation control to offer a sustainable alternative.
Several scholars have explored the creation, or "cultivation", of such a new matter; among them, Alexander Bismarck and Mitchell Jones of the University of Vienna gave a significant contribution to researching the use of fungal species to create sustainable alternatives to traditional leather (Jones et al., 2020). Their work focuses on producing skin-like materials using agricultural by-products, such as sawdust, which are colonized by fungal mycelium. Their research has only recently become integrated with additive manufacturing, presenting promising prospects for configuring a fashion system able to merge the advantages of a digital supply chain with the use of biomaterials.
In recent years, the fashion world has witnessed numerous experiments in a larger, more commercial direction. The California-based biotechnology company MycoWorks pioneered this sector, specializing in producing leather-like materials using mycelium, the root structure of fungi (MycoWorks, 2024) [Fig.02]. The mycelium cultivation process is inherently circular: the material grows using organic waste and is produced with minimal water and energy consumption. This material offers an ethical and ecological solution and has excellent technical properties such as durability and adaptability. In September 2023, MycoWorks opened the world's first commercial-scale Fine Mycelium™ production facility in South Carolina, which enables the cultivation of a 136,000-square-foot plant to supply millions of square feet of Reishi™ annually to luxury industry partners, marking a significant step toward scaling sustainable materials in the fashion market. The company has also partnered with Hermès to create sustainable luxury products, demonstrating the scalability and applicability of mycelium in the high-end fashion industry (Il Sole 24 Ore, 2023).

One of the most commercially successful examples is Stella McCartney's collaboration with Bolt Threads, which produces bio-derived materials. Stella McCartney has long been a pioneer in sustainable fashion, and her recent commitment to using biomaterials is another step forward. The designer has adopted Mylo, a soft and flexible innovative material derived from mycelium, and integrated advanced digital supply chain to ensure transparency and efficiency throughout the production phase. In 2022, Stella McCartney launched the Frayme Mylo bag, the first luxury accessory made with this material. Through digital traceability, McCartney can track the origin of materials and production processes, ensuring that each step complies with social and environmental responsibility principles (Phyta Biodesign, 2022).
The materials analyzed are all linked by the filrouge of generating a virtuous circle for the entire ecosystem; indeed, as Kate Fletcher (2014) points out, sustainable fashion is related to its production process and their potential to regenerate environmental resources. The challenge shifts from minimizing the impact of fashion on natural ecosystems to finding new paths to actually take part in it constructively.

The rise of a Systemic Model
Just recently, digital manufacturing has been brought into synergy with bio-growing materials and embodies the potential of technology to revolutionize fashion design and production by enabling on-demand production, reducing waste, lowering transportation emissions with localized manufacturing, and fostering design customization. In line with these possibilities offered by the digital supply chain, the fashion industry has started to explore new ways of combining technological innovation and sustainability, redefining materials and production processes.
Simplifyber and Scarlett Yang are pioneering the integration of biomaterials and 3D printing in fashion, creating a valuable alternative to traditional textile manufacturing like spinning, weaving, cutting, and sewing. The process involves a liquid cellulose solution derived from plant-based materials, such as wood pulp, which is poured into moulds and dried into biodegradable products. This method reduces traditional manufacturing steps by 60% and cuts material waste by 35% (3D Printing Industry, 2022). The final garments are non-toxic and 100% natural, ensuring they can be recycled like paper (PR Newswire, 2022).
Similarly, Scarlett Yang uses algae extract and silk cocoon protein to create biodegradable textiles that respond to environmental conditions like humidity and temperature, altering their shape dynamically. These garments decompose entirely in water within 24 hours, making them an exemplary case of closed-loop sustainability (Specialty Fabrics Review, 2021). Her project, "Decomposition of Materiality," integrates bio-design, digital fabrication, and 3D generative simulation to produce garments with minimal waste and maximum sustainability (Yang, n.d.).
Simplifyber and Scarlett Yang exemplify this shift, showcasing methods that significantly reduce waste and energy consumption, aligning with the principles of closed-loop sustainability (3D Printing Industry, 2022; Specialty Fabrics Review, 2021), setting a new standard for the industry.

Navigating the challenges
Integrating advanced technologies and innovative materials in fashion only sporadically reaches commercial levels, remaining largely confined to experimental. The high costs associated with research, development, and production, combined with scalability issues and resistance to disrupting traditional industry practices, place these advancements firmly within niches of speculation and experimentation. The extended production timelines, alongside challenges related to durability and washability, further hinder their transition to broader industrial and commercial applications. A

sustainable fashion model requires a scalable approach to different production realities, from large global brands to small local companies. This situation poses particular challenges for small and medium-sized enterprises (SMEs), which risk being excluded from these innovations, further entrenching their reliance on unsustainable practices and exacerbating global inequalities (Ellen MacArthur Foundation, 2017).
Despite these hurdles, investments in bio-based materials within the fashion sector are steadily rising: the vegan leather market is projected to approach a valuation of $90 billion by 2025 (Grand View Research, 2022), and recent surveys also reveal that 90% of respondents favour the use of next-generation leathers, with 62% willing to pay a premium for such products, particularly among Generation X and Millennials (Material Innovation Initiative, 2021). The nascent commercialization of bio-based fashion through digital production embodies the germination of a future where the confluence of innovation, ethics, and environmental consciousness redefines the very fabric of human creativity and its relationship with the planet.

Conclusions

As an industry and cultural phenomenon, fashion is a crucial point of departure for addressing the challenges of the post-anthropocene. The paper highlighted both the opportunities offered by the adoption of biomaterials and additive digital manufacturing production model and the structural and ethical limitations that hinder their systemic diffusion. “Thinking together with technologies and species invites us to imagine a common future”, with these words Donna Haraway (2016, p.58) suggest a paradigm of *simpoiesis* based on collaboration and interconnection in which fashion can be reinterpreted as a hybrid system where technological innovation and sustainability successfully converge. Emerging technologies offer tools to pave the way in this direction reducing waste, improving transparency, and responding to an increasingly awareness-driven market. However, as Jason W. Moore (2015, p.123) points out: “Sustainability cannot be a luxury; it must be the framework of production itself” implying more than the simple introduction of technical innovations is needed if they remain trapped in a linear economic model.
The transition to sustainable fashion requires a systemic change that implies a profound rethinking of the relationship between production, consumption and nature. Bruno Latour (2017) invites to reconsider our place in this ecosystem through his text "Third Landscape", recognizing that the survival of humanity is linked to an ethical coexistence with the planet: “We cannot think of modernity without reconsidering our place within the terrestrial system” (Latour, 2018, p.45). Fashion, as a cultural expression and production system, can become a tangible example of this new alliance, integrating the principles of regeneration and environmental respect.
Cultural change will be a key element: Consumers should be educated to see their purchases not as status symbols but as acts of responsibility towards the environment and future generations. Indeed fashion, in its deepest essence, is not only a reflection of our time but a promise of what we could become: a humanity capable of weaving not only clothes but bonds of respect and harmony with the planet we call home. In a world desperately trying to balance innovation and sustainability, Suzanne Lee's work reminds us that: We are not simply making clothes; we are cultivating a new vision of fashion, where biology becomes our most powerful creative tool (Lee, 2007).

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Images
Fig. 01

Fig. 02

Fig. 03

Captions

Fig. 01 – Biocouture collection by Susanne Lee, 2013. These jackets are entirely hand-stiched from grown bacterial cellulose using a stenciled fruit print, using a mix of blueberrie and beetroots.ù

Fig. 02 - MycoWorks' proprietary Fine Mycelium™, platform has enabled a new class of premium, non-animal materials that are the next evolution in mycelium.

Fig. 03 – The founders of Simplyfiber, Maria Intscher and Owrang Phil Cohen. New York brand first product is a 3d printed and 100% biodegradable shoe.