Fashion's future: the power of biomaterials and digital manufacturing for systemic sustainability

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Michela Musto, https://orcid.org/0000-0003-0700-8024 michela.musto@unicampania.it
Department of Architecture and Industrial Design, Università degli Studi della Campania "Luigi Vanvitelli", Italy

Abstract. In an era where fashion mirrors the excesses of a society driven by disposability, the garment emerges as a transformative device to reimagine our relationship with identity, technology, and the environment. This paper delves into the transformative potential of biomaterials and digital manufacturing in redefining fashion as a sustainable and ethical practice. Situated within the post-Anthropocene discourse, the analysis interrogates the environmental and social implications of these innovations, weaving together theoretical perspectives and exemplary case studies that illuminate the convergence of living matter and additive technologies as a space for new ontologies and aesthetic possibilities. 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.

Introduction

Fashion, in its essence, has always been more than mere clothing, it is a codified language, a dynamic intersection of materiality and meaning, power and resistance, ephemerality and permanence. Across history, garments have functioned as socio-political statements, markers of identity, and repositories of collective memory. Yet, within the rationale of late capitalism, fashion has undergone a profound ontological shift, increasingly alienated from its artisanal roots and cultural significance. Baudrillard describes fashion as a simulacrum: a self-referential system that thrives on perpetual reinvention, where obsolescence is not an accident but a structural necessity (Baudrillard, 1970). In this hyper-consumerist paradigm, garments cease to be objects of use and, instead, become fleeting signs in an accelerating cycle of production, consumption, and disposal. The consequences are tangible: ecological devastation, labour exploitation, and an erosion of craftsmanship in favour of algorithmic trends and mechanised excess. By examining the potential of emergent technologies to recalibrate the ethics and aesthetics of fashion, this paper interrogates these tensions while exploring whether a paradigm shift that reconciles sustainability with innovation, material intelligence with human agency, is not only possible but imperative.

In the context of the post-Anthropocene era, Morton's philosophical concept of "hyperobject" appears particularly adequate to frame a contemporary understanding of what fashion is today, namely a complex, widespread, and interconnected system (Morton, 2013). 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 of the fashion industry on our ecosystems are now well-known, and these data are well established. Indeed, the fashion industry contributes to 10% of global carbon emissions and to 20% of water pollution (McKinsey, 2020), making it one of the most urgent industrial sectors for action. The research on new materials and manufacturing technologies offers unprecedented opportunities to address this crisis; the one evaluated in this paper relates to this intersection and the potential of biomaterials to redefine the very concept of fashion, mitigate damages, and actively contribute to ecosystem regeneration (Everett, 2022).

Contemporary fashion reflects a system of overproduction fuelled by an economic model that prioritises immediate profit over sustainability. The fast fashion culture embodies what Guy Debord calls the "société du spectacle", where the production of ephemeral goods and the image take on greater value than the intrinsic one (Debord, 1967). This approach embodies the 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 involves many fields of competence; among these, biologists took significant traction, giving rise to a rapidly evolving field of "biodesign". This area of design employs living materials, such as cultured tissues and microorganisms, to support the vision of organic design, allowing nature to shape objects following 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 progress and terrestrial co-existence. This shift pushes design into the moral realm, provoking reflection on deeply ingrained beliefs and ethical considerations (Myers, 2019).

This contribution seeks to situate itself at the convergence of these experimental domains, aiming to critically interrogate the role of biobased textiles in fashion as agents of transformation, shifting fashion to a paradigm of resilience and symbiosis (Papanek, 1985).

Rethinking sustainability beyond the Anthropocene

In response to the current state of affairs, numerous critical movements have come into being. Kate Fletcher points out that fashion, as a cultural and industrial phenomenon, has the potential to drive systemic change (Fletcher, 2014), 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).

In line with this movement, designers wield significant power by crafting scenarios and prototypes that influence behaviour.

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01 | Biocouture collection by Susanne Lee, 2013. These jackets are entirely hand-stitched from grown bacterial cellulose using a stencilled fruit print created with a mix of blueberries and beetroots, Credits: Susanne Lee

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Michel Serres, in his work *Le contrat naturel*, calls for a "natural contract" between humanity and the planet, recognising the need for an ethical balance between production and sustainability, acknowledging the deep relationships between human and natural ecosystems, which are, and should not be, distinguishable anymore (Serres, 1990). Indeed, as Parisi argued, biomaterials disrupt the linear narrative of production and waste, suggesting a cyclical temporality that aligns with ecological interdependence rather than industrial determinism (Parisi, 2021). 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 an entangled vision of fashion design. 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

While conventional textiles remain tethered to plant-derived fibres or petrochemical synthesis, innovative explorations, such as *BioCouture* by Susanne Lee, are among the first to manifest tangible applications and to interrogate the potential of microorganisms as architects of biomaterials, not only for fashion but for broader material ecologies (Fig. 1). Through the alchemy of fermentation, bacteria orchestrate the assembly of cellulose microfibrils, yielding a supple, compostable medium that, like its traditional counterparts, can be shaped and sewn, yet signifying a profound ontological transformation in how we conceive textiles and engage with them (Lee, 2013).

Despite the disruptive meaning of this project, self-growing materials still need to be improved in terms of durability, water resistance, and biodegradation control to offer a sustainable commercial alternative.

Several scholars have explored the creation, or 'cultivation', of such a new material. Alexander Bismarck and Mitchell Jones of the University of Vienna contributed significantly 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 colonised 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. Digital fabrication operates in this area as a morphogenetic vector, capable of shaping growth environments and support structures for biomaterials, enabling hybrid forms to emerge. Beyond mere formal replication, additive and subtractive digital technologies articulate a situated and responsive design practice, one that embraces the unpredictability and autonomy of living matter, giving rise to artefacts that are simultaneously designed and cultivated.

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, specialising in producing leather-like materials using mycelium, the root structure of fungi (MycoWorks, 2024) (Fig. 2). The mycelium cultivation process is inherently circular. The material grows using organic waste and is produced with minimal water and energy consumption. This material 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. The 136,000-square-foot plant enables the cultivation of Reishi™, supplying millions of square feet annually to luxury

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

03 | The founders of Simplyfiber, Maria Intscher and Owrang Phil Cohen. New York brand first product is a 3D printed and 100% biodegradable shoe, Credits: Simplyfiber

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industry partners, a significant milestone in scaling sustainable materials within the fashion market. The company has also partnered with Hermès and Stella McCartney to create sustainable luxury products, demonstrating the scalability and applicability of mycelium in the high-end fashion industry (Casadei, 2023).
Stella McCartney has long been a pioneer in sustainable fashion, and her recent commitment to using biomaterials is another step forward. In 2022, Stella McCartney launched the Frayme Mylo bag, the first luxury accessory made with biomaterial (Stella McCartney, 2023). The designer has adopted Mylo, a soft and flexible innovative material derived from mycelium (85%) and and lyocell (15%), a regenerated cellulose fibres material. The mycelium is harvested as a 'foamy layer', uniquely mimicking the microstructure of collagen, giving the final material a supple warmth and sponginess not achievable otherwise with fully synthetic option. Through digital traceability, McCartney can record the origin of materials and production processes, ensuring that each step complies with social and environmental responsibility principles (Kele, 2023).
The materials analysed are all linked by the *fil rouge* of generating a virtuous circle for the entire ecosystem. Indeed, as Kate Fletcher points out, sustainable fashion is related to its production process and its potential to regenerate environmental resources (Fletcher, 2014). The challenge shifts from minimising the impact of fashion on natural ecosystems to finding new paths to actually take part in it constructively.

The rise of a Systemic Model

The recent convergence of digital manufacturing and biogrown materials has emerged as a *locus* of profound transformation, embodying the potential of technology to radically reconfigure fashion's ontological and material foundations. This synergy heralds a paradigm shift, enabling on-demand production, mitigating waste, diminishing transportation emissions through localised fabrication, and fostering unprecedented avenues for sustainability. Within this evolving landscape, the fashion industry is actively interrogating the interplay between technological innovation and sustainability, reimagining both the substance of materials and the very *ethos* of production itself. Simplifyber and Scarlett Yang are an example of pioneering the integration of biomaterials and 3D printing, creating an alternative to traditional textile manufacturing like spinning, weaving, cutting, and sewing (Fig. 3). The process makes use of 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% (Everett, 2022). The final garments are non-toxic and 100% natural, ensuring they can be fully recycled (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 digital simulation software to produce garments with minimal waste (Yang, n.d.). Digital fabrication enables indeed the integration of environmental sensing systems, such as humidity, temperature, and pH sensors, directly into the manufacturing workflow, allowing the real-time modulation of growth conditions and structural parameters in biomaterial-based design. Through closed-loop feedback systems, environmental data can be translated into computational inputs that guide material deposition, nutrient diffusion, or structural porosity, resulting in artefacts that dynamically adapt to their surroundings during the fabrication process itself.

The cases of Simplifyber and Scarlett Yang showcasing methods that significantly align with the principles of closed-loop sustainability (Everett, 2022), setting a new standard for the industry.

The adoption of biomaterials and digital manufacturing must not remain confined to isolated case studies but rather be embedded within a structured implementation framework. At an operational level, this necessitates 'incentives for enterprises' to transition towards additive manufacturing and bio-based materials, 'regulatory frameworks' that enforce supply chain transparency and digital traceability, and 'educational programmes' designed to equip emerging designers and manufacturers with expertise in bio-fabrication and advanced sustainability practices. The systemic transformation of fashion requires not only technological advancements but also a restructuring of the industry's socio-economic fabric, aligning sustainability with economic feasibility.

Navigating the challenges

The integration of advanced technologies and novel materials in fashion remains, for the most part, an ephemeral incursion into the commercial realm, rooted in experimentation rather than in systemic transformation. The prohibitive costs of research, development, and production, coupled with the inherent challenges of scalability and the inertia of entrenched industry paradigms, relegate these innovations to the margins of speculative practice. Furthermore, the temporal lag in production, alongside unresolved issues of durability and washability, complicates their migration into broader industrial and commercial circuits. A truly sustainable fashion model necessitates a scalable approach that accommodates the diverse realities of production, from global conglomerates to small, local enterprises. Yet, this imperative is fraught with asymmetries. Indeed, small and medium-sized enterprises (SMEs), constrained by structural limitations, risk exclusion from these technological advancements, thereby perpetuating dependence on unsustainable modes of production 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. The nascent commercialisation 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 the opportunities offered by the adoption of biomaterials and the additive digital manufacturing production model, besides 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) suggests 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 by reducing waste, improving transparency, and responding to an increasingly awareness-driven market. However, as Jason W. Moore (2015) points out: «Sustainability cannot be a luxury; it must be the framework of production itself», thus implying that more than the simple introduction of technical innovations is needed, if they remain trapped in a linear economic model.

The transition to sustainable fashion necessitates a radical paradigm shift, one that reconfigures our understanding of the interconnected triad of production, consumption, and nature. In this context, Bruno Latour (2017) invites us to reimagine humanity's position within the ecological web in "Third Landscape", arguing that our collective survival hinges upon an ethical mode of coexistence with the planet. This ontological realignment requires us to move beyond anthropocentric paradigms, recognising that fashion, as both a cultural and material practice, must align itself with the rhythms and limitations of the Earth: «We cannot think of modernity without reconsidering our place within the terrestrial system» (Latour, 2018). Fashion, as a cultural expression and production system, can

become a tangible example of this new alliance, integrating the principles of regeneration and environmental care.

However, this shift cannot be solely technological. It must be deeply cultural, reshaping not only the materials and methods of production but also the very way we perceive and engage with fashion as a social and ecological act. Cultural transformation will indeed be pivotal. Consumers must be reoriented to perceive their purchases not as mere status markers, but as ethical gestures, acts of accountability toward the environment and future generations. Fashion, in its most profound essence, is not merely a mirror of the present but a projection of our potential, a promise of what we might yet become, namely a humanity capable of weaving garments and of interlacing relationships founded on respect and symbiosis with the Earth. In a world precariously balancing innovation and sustainability, Suzanne Lee's work serves as a potent reminder that we are not merely producing clothing. We are cultivating a paradigm shift, wherein biology emerges as the most profound and generative force in the reimagination of fashion (Lee, 2007).

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