# FAMILIARIZING WITH FUNGI FOR THE TEXTILE SECTOR

## A FIRST-PERSON JOURNEY INTO NEW MATERIALIST TECHNOLOGIES, FROM LEATHER TO YARN

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**Abstract**

Fungi are called into action to engage in the literary debate on new materialism and sustainable technologies, proposing an alternative ontology, due to the discussions they have increasingly sparked across various disciplines in recent years. Specifically, the growing interest towards fungi and the fungal world has contaminated fashion, challenging textile research and its supply chain. The phenomenon that intertwines fungi and fashion therefore calls for a deeper understanding of their role and implications for both fashion theories and design practices.
As a consequence, this interdisciplinary study aims to illustrate the main material typologies, their processing and the impacts of these tangible applications, highlighting fungal leather as a viable alternative to conventional animal leather.
This study offers insights into global recent material innovations, exploring how the market and consumers perceive these next-generation materials, as well as how they adapt to the existing fashion supply chain. Framed within the new materialist theoretical perspective, which urges a return to the intrinsic material value of goods and their experiences, the study aims to enhance the entanglement among the multitude of actors in the ecological system: humans, technologies and materials. To decentralize the human perspective, this study is written in the first person by fungi (e.g. “we fungi”) and aims to provide a deeper technical comprehension of the nature of their raw material sources. We fungi advocate for being recognized not as passive resources but as active contributors to low-impact production processes, emphasizing the need for a closer dialogue between designers and material scientists.

**Keywords**: *Fungi; Fungal Leather; Sustainability; Material R&D; New Materialism*

## EVERYONE’S CRAZY ABOUT US MUSHROOMS

Historically, we fungi have often been relegated to the background compared to the fascination that has seen ferns and algae being collected in herbariums for aesthetic pleasure (Ehrman and Watson, 2018; Hunt, 2005). Indeed, since ancient times, we have been useful to humans not only for dietary purposes, but also linked to psychotropic rituals influencing the arts (Samorini, 2001) and used for therapeutic purposes through the so-called mycotherapy (Cocchi and Siniscalco, 2013).
More recently, our role has expanded to include soil regeneration or mycoremediation and has inspired the literary debate in rather novel ways. In fact, since 2019, there has been a significant increase in interest regarding our way of life and our adaptability to human uses. Besides seeing mycological books like Merlin Sheldrake’s (2020) become bestsellers, in various disciplinary fields we have become the subject of a growing curiosity. To name a few examples: within anthropology the book by Anna Tsing (2015), within popular culture and subcultural communities the book by Doug Bierend (2021), within cultural and gender studies the book by Yasmine Ostendorf-Rodríguez (2023). This phenomenon has led to the emergence of a mycophilia even within fashion studies and design. Focusing on our tangible material manifestation, rather than as a decorative motif – such as the psychedelic prints popularized by the Hippie movement in the 1970s that inspired Stella

McCartney Summer 2022 Fashion Fungi collection – there is still confusion. Therefore, our first-person contribution, enriched by on-site visits and discussions, aims to clarify our role in the contemporary fashion industry. We seek to reconstruct the complex interplay inherent in this hybrid subject by spanning various disciplinary fields – textile engineering, material science, biology, corporate and market sustainability reports – to propose new ways to fruitfully intertwine with fashion theories and design practices. According to the new materialist theoretical perspective, which interprets the current epoch as characterized by an ongoing "material turn," it is not surprising that our role as fashion design material source requires deeper analysis. In this context, the work of Anneke Smelik (2018) interweaves new materialism with the posthuman philosophy to analyze unique fashion design practices that highlight the entangled nature of humans, technologies and materials (both organic and inorganic). As fungi, it is crucial to explain the insights we offer towards low-impact production processes and to advocate for not being treated as another of nature's passive resources to be exploited and extinguished by human will. To this end, the objective of our contribution is to provide a clear and detailed overview of our typologies and their corresponding impact, primarily focusing on fungal leather as an alternative to conventional animal leather. We hope that increased knowledge in the field will foster a more effective dialogue between designers and material researchers, leading to product embodiments that respect the cultural heritage, the planet and the precious interrelations among all beings.

## METHODOLOGY

This study is supported by the literature and on-site visits, as well as attendance at seminars and various meetings with material scientists, technicians, designers, textile engineers and mycologists. These activities were part of the doctoral research conducted by Clizia Moradei at Università Iuav di Venezia between 2021 and 2024.

Notable on-site visits include six months of fieldwork at the Italian material R&D center Pangaia Grado Zero, dedicated to implement Muskin leather, and a visit to the Biotechnology Lab at the University of Borås (Sweden), which focuses on developing fungal leather and yarn. Key meetings include discussions with a representa from the Chinese material R&D center Pureway Biotechnology, which is launching mycelium leather, and conversations with mycologist Enrico Bizio, one of the founders of the Società Veneziana di Micologia.

To introduce the material content of the study, it branches out from our two identified typologies, which will be analyzed in detail, namely fungal leather (comprising two sub-categories form mycelium and fruiting body) and fungal yarn. Beyond outlining the main properties, significant emphasis will be placed on the processes to provide a clear overview that can guide not only non-scientists, such as fashion designers and product developers, but also fashion theorists seeking to engage with the topic. The common characteristics of these innovations are: the companies' efforts to preserve the natural quality of our original resources to reduce the environmental impact of material waste; and the promotion of small-scale production, which, though it may appear limiting, offers an opportunity for a paradigm shift that is less human-centered. These characteristics define these approaches to material innovation as new materialist technologies.

## OUR TANGIBLE POTENTIAL

When discussing us fungi in the fashion industry the reference is to the leather market[1], which, measured in terms of bovine, ovine, caprine and buffalo hides, had a global production volume of approximately 13.4 million tons in 2022 (Textile Exchange, 2023: 6). However, year by year since 2020, online searches for leather have decreased by 3.5%, while those for vegan leather have increased by 69% (Hakansson et al., 2023: 13). Collective Fashion Justice and Material Innovation Initiative have proposed the 2023 report that investigates the future and alternatives to animal leather, revealing that 75% of Australians, almost 78% of British and 90% of Chinese respondents would prefer, given the choice, non-animal leather made from next-generation materials (Hakansson et al., 2023: 14–15). Consumers' answers highlight the growing awareness of the negative impact of the tanning industry on ethical and environmental issues and offer the opportunity for the fashion industry to guide them towards more responsible choices.

1 Their raw material prices are also equivalent to the luxury leather market.

Comparing the impact of animal leather with synthetic and next-generation leather, the CO2 emissions per $m^2$ of material produced are: bovine leather 110 kg, PU/synthetics 7-15.8 kg, bio-based PU 8.2 kg, Mirum[2] 0.8-2.1 kg (Hakansson et al., 2023: 19). From 2013 to 2022, new companies engaged in developing next-generation leathers and their total grew from 18 to 65 (Hakansson et al., 2023: 23). Material Innovation Initiative includes in the category of next-generation materials those with a biomass percentage greater than 50%: plant-derived, mycelium, cultured animal cells, microbial cultures, recycled materials and blends (Hakansson et al., 2023: 11).
A group of biopolymers are those in which plant biomass (pineapple fiber, cactus leaves, apple scraps and others) is combined with for 30-80% polylactic acid PLA (a biodegradable thermoplastic polymer of biological origin) mixed with PHA (polyesters naturally produced by microorganisms), PBS (an aqueous saline solution that ensures flexibility) or frequently with conventional polymers (Gullingsgrud, 2023: 90–99: 110). A second group of biopolymers, still in the experimental stage, are obtained from the fermentation of microorganisms, such as bacterial cellulose. Mycelium and fungal fruit body leather do not fall by definition under these two categories. In the first case, this is because they are not fibers but microfibers, and in the second case, because they are not produced from a natural fermentation process of microorganisms. Nonetheless, our leather manifestations are closely akin that they belong to the same category of bio-based leathers. Similarities reside in the tactile and aesthetic level; whereas differences reside in our strong commitment to promote production systems powered by renewable energy and more symbiotic material-designer developmental processes.
Cataloging and describing the diverse types and ongoing experimental technologies of fungal-based leathers is not an easy task. This difficulty arises from several factors, often underscored and critiqued by industry insiders, including: the complexity of the literature on the subject, the industrial secrecy and limited disclosure of Technology Readiness Level (TRL) data by supplier representatives. These obstacles obstruct clear communication with designers and consumers, thereby contributing to the greenwashing trend. Thus, a first-hand exploration of our world – touching our material samples and visiting our production sites – is essential.
After a notable downturn starting in 2022, exacerbated by Bolt Threads' cessation of production in July 2023 (Bittau, 2023), investments in start-ups developing materials such as plant-based and lab-grown leather, silk and fur reached $500 million in 2023 – a nearly 10% increase from the previous year; although these numbers are lower than the record $1.1 billion in investments reached in 2021, it is promising news for the sector (Kent, 2024; Material Innovation Initiative, 2024).

## MYCELIUM LEATHER

For mycelium production we fungi are grown in automated vertical cultivation on a solid substrate (solid fermentation) or in bioreactors[3] on a liquid substrate (liquid or submerged fermentation) (Gandia et al., 2021) (fig. 1). The composition of the substrate maintains the characteristics of the natural substrate; therefore it is plant-based and usually uses industrial waste, such as rice husk, cotton waste, straw or sawdust[4]. The distinction between the two techniques lies in the fact that in the former case, cultivation time is slower but more advanced level of technical and quantitative scalability has been achieved, whereas in the latter case, cultivation is faster but its scalability is constrained. While solid-state cultivation requires approximately two weeks for mycelium cultivation and growth to yield a mycelium sheet, liquid-state cultivation requires only two days, followed by biomass drying phase for storage[5]. Our most commonly used fungal varieties are: saprophytic and parasitic fungi in solid fermentation, where our fruits are continuously harvested to encourage mycelial proliferation; filamentous fungi in liquid

2 Plant-based leather introduced by Natural Fiber Welding.

3 Similar to the ones uses for brewing.

4 Even if the variety cultivated is an edible mushroom, to consider a product edible it must grow on a cultivation substrate that is in accordance with certain certifications. As a result, the fruiting products of these crops generally constitute biodegradable waste.

5 It should be noted that biomass is processed wet and stored in frozen state into refrigerators, therefore, it is rarely dried. 20 kg of wet mycelium correspond to 5 kg of dried mycelium, which is equal to the volume of approximately eleven full plastic shopping bags.

Fig. 01

fermentation, commonly known as molds, which spontaneously do not produce fruiting bodies. Cultivation occurs in a controlled environment that ensures mycelium purity, isolating it from contaminating agents such as other molds, yeasts and bacteria. The mycelial hyphae, extracted and collected by biologists in Petri dishes, naturally possess a foamy texture due to the flow of protoplasm. Enzyme action then creates a lignocellulosic material film, which is subsequently dried to preserve its obtained shape (Jegadeesh et al., 2022: 2; Kumla et al., 2020). This mycelium film is known as compressed mycelium, a rectangular sheet of variable dimensions[1]. In the most advanced stage developed by the R&D center MycoWorks, the base fabric, which enhances the material's strength, is made of vegetable fibers integrated into a single layer thanks to the hyphae growing around and inside them through liquid fermentation (Mycoworks, n.d.)[2]. This process avoids adhesives for subsequent fabric lamination, as implied by solid fermentation. However, the majority of mycelium leather alternatives belong to the category of laminated nonwoven textiles. Because mycelial cellular components are not constant, atmospheric agents can cause degradation. Thus, plasticization, cross-linking processes and other surface finishing applications are necessary yet critical to align with the objective of reducing environmental impact while preserving the natural quality of the raw biomass (Jegadeesh et al., 2022). The bioengineering of the mycelial root apparatus, distinctive to each producer, could potentially

1 The manufacturer Pureway Biotechnology, for example, markets it in the size of 80X45 cm.

2 To learn about MycoWorks' mycelium manufacturing process, watching the video on the center's website is recommended.

allow for future 'programming' based on required properties and avoiding subsequent harmful treatments.
Among the pioneers of mycelium leather are the material R&D centers: Bolt Threads with Mylo, MycoWorks with Reishi, Mogu and Squim with Ephea™, Ecovative with the AirMycelium technology. Apart from Mogu that is based in Italy, the others are located in the United States (the first two in California, the latter in New York State). However, it should be noted that in recent years, China has contributed for the 75% to global mycelium production (Straits research, n.d.). Proof of this is the Chinese material R&D center Pureway Biotechnology, which launched Meri™ in Spring 2024. An interesting pilot-scale example is also the VTT Technical Research Center of Finland that developed a technology for the continuous mycelium film production resembling latex membrane (Vandelook at al., 2021).
Mylo was adopted by Adidas in 2020 for the Stan Smith sneakers model and by Stella McCartney for a selection of garments and accessories. A further development of Reishi, named Sylvania, in 2021 embodied Hermès' Victoria bag, remaining in prototype stage (Lottersberger and Celeste, 2021). MycoWorks' Reishi is considered the first mycelium leather to meet the luxury fashion industry standards, as Fine Mycelium™ technology allows it to undergo the same artisanal treatments as animal leather (Mycoworks, 2023). Lastly, Ephea™ was adopted for outerwear and accessories by Balenciaga's Fall/Winter 2022-23 collection.

## AMADOU LEATHER

Another type of fungal leather is primarily derived from the fruiting body of the fungi Fomes Fomentarius or Phellinus, from parasitic or saprophytic fungal varieties, it is also known as Amadou fungus, Hoof fungus or Tinder fungus (Darabán, 2022). Traces of it have been found in Neanderthal man remains, indicating its likely historical use as tinder for fire (Marinis and Brillante, 1998: 102–120; Raimondi, 2006: 26). The material obtained from the Amadou fungus is referred to as Amadou Leather or German Felt.

Fig. 02

Aesthetically, it resembles suede leather with a slight iridescent effect and irregular striations, while its unique feature is its extreme softness to the touch. It is biodegradable (Bustillos et al., 2020), highly absorbent, antibacterial (Kolundžić et al., 2016; Seniuk et al., 2017) and has poor mechanical properties (Bustillos et al., 2020; Meyer et al., 2021). It is an irregular, fragile material with a natural aesthetic and it is difficult to dye. These limitations are posing significant challenges today.
Separated from the plant on which it thrives, processing begins with manual knife peeling of the fruiting body (fig. 2). The outer shell, extremely woody, is currently discarded. The soft central pulp is boiled and steamed, then manually stretched and thinned before being further pressed. The resulting pieces, which roughly correspond to the size of the original fruiting body, are hung to dry. This drying process sometimes leaves marks from clothespins on the edges of the samples. The samples are frozen at -25°C for two weeks to eliminate any insects or larvae inside. After quarantine, they are thawed and stored in non-airtight boxes[1].
In Europe, Amadou leather has been used as hemostatic absorbents, oral tampons, bend-aids, clothing items, body ornaments (jewelry), accessories (bags, gloves, hats), fly-drying pads for fishing, burned for its sedative effect on animals and insects, as well as bottle corks (Ainsworth, 1976; Gandia et al., 2021; Harding, 2008; Papp et al., 2017; Schmidt, 2006; Schwarze, 2013; Stamets, 2005). In central European regions like Bavaria, Thuringia and ancient Bohemia, it was produced in quantities reaching 50 tons annually until 1890 (Schmidt, 2006). Today, it is still produced in the

1 The full manufacturing process has been reconstructed thanks to the information generously shared by Pangaia Grado Zero.

Fig. 03

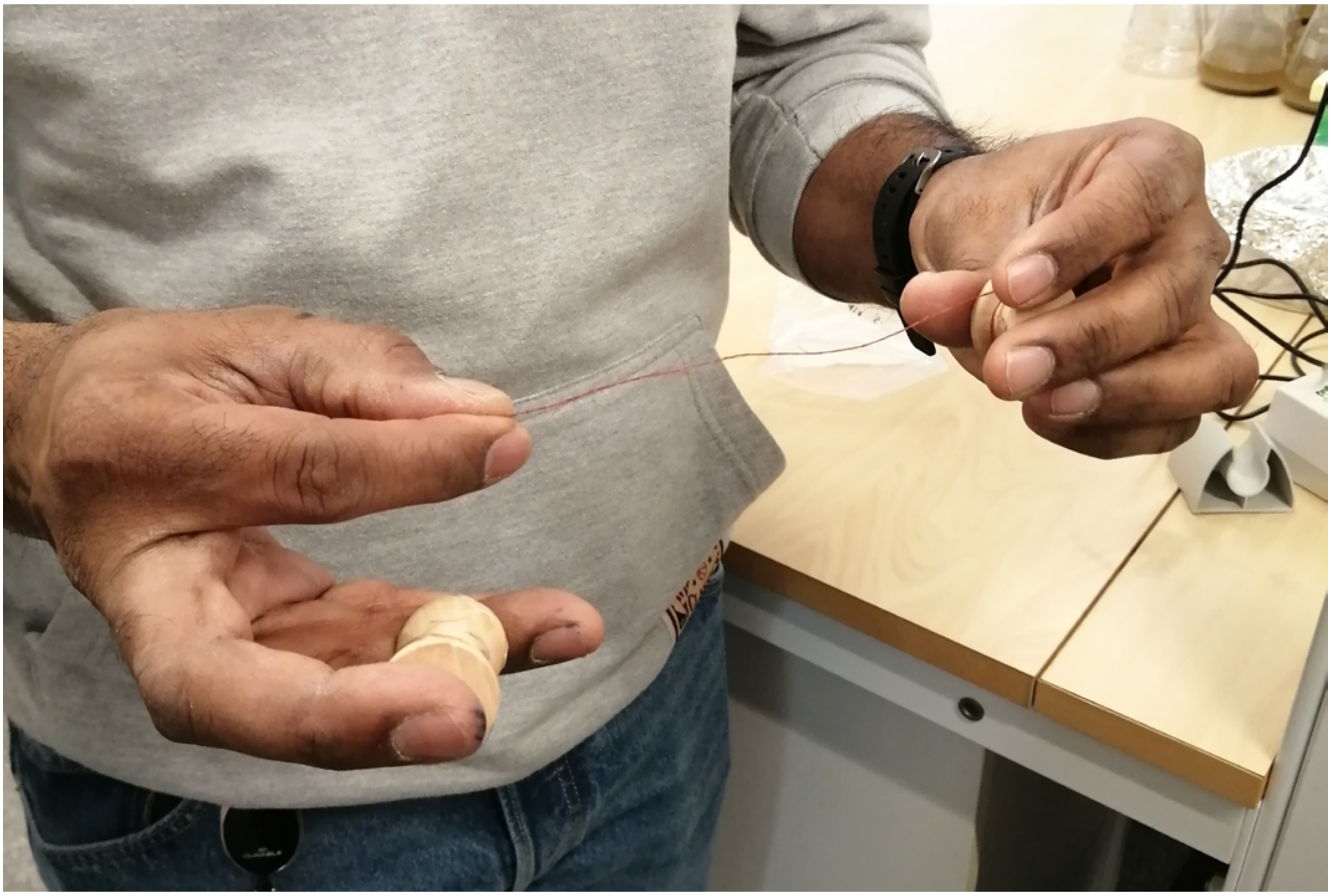

Fig. 04

rural areas of Bohemia and Transylvania (Papp et al., 2017; Stamets, 2005). Studies indicate that the Toplàsz people of Corund in Transylvania still work with Amadou from Fomes Fomentarius and Fomitopsis Betulinus, harvested in July and August (Papp et al., 2017). Amadou processing is limited to small-scale artisanal production, and its products are locally known but less recognized globally. As documented by Finnish designer and doctoral candidate Mari Koppanen, focusing on the story of Mr. Imre, one of the oldest craftsmen in the village of Corund, this knowledge has been passed down through generations and is nowadays at risk of extinction (Koppanen et al., 2023). There are very few intermediaries who trade the raw material; in addition, online trading platforms for finished products evidence their naive artisanal nature, limiting the appeal to the fashion industry. Conversely, significant is the work of Life Materials, division of the Italian material R&D center Pangaia Grado Zero, which trades it as Muskin. Life Materials not only takes care of its commercial distribution but also is committed to implement and scale Muskin for the industry. The challenge is to re-convert the existing textile supply chain by leveraging the expertise and machinery of local tanning industries (fig. 3).

## FUNGAL YARN

In rare cases, we fungi appear as filament for yarn. In fact, we are not yet commercially available in such a state, however ongoing experimentation continues to explore our potential. The project coordinated by Professor Akram Zamani at the Biotechnology Lab of the University of Borås in Sweden (January 1, 2019 - January 16, 2023) encompasses various research branches aimed at contributing to the reuse of agri-food industry waste (particularly bread), used as cultivation substrates for fungi[2]. One branch of the research unit focuses on obtaining fungal yarn and nonwoven textiles from fungi, using respectively

2 The details of the project and process come from the on-site visit to their laboratory on April 4, 2024.

wet spinning and wet laying processes (liquid fermentation). The outcomes include samples of twisted yarn approximately 20 cm long, which to the touch resemble rough paper yarn (fig. 4). Unfortunately, scalability limitations of such experimentation hinder its application potential for design prototypes. This fiber appears promising for medical applications due to its antibacterial properties, skin compatibility and soothing effect.

## DISCUSSION

In regard to the environmental issue, the application of our leather and yarn alternatives in material technology is gaining traction because of its high biocompatibility and renewability, as well as its affordable – ease of biomass cultivation and short growth period – and carbon-neutral growth processes (Amobonye et al., 2023). Accordingly, Louis Quijano et al. (2021: 901) claim that the chemical production of bio-based equivalents of synthetic fibers has its pros, nonetheless, also its cons: the advantage is that the production of biosynthetic fibers reduces the ecological impacts and overreliance of non-renewable resources, the disadvantage is the argument that states how biosynthetic fibers indulge the issue of overproduction to comply with the market.

In disagreement with the second aspect and except for the case of yarn, by virtue of the fieldwork and visits it is argued that the small-size R&D realities presented in the study like Pangaia Grado Zero, Pureway Biotechnology and the VTT Center, are able to challenge the productive paradigm. This is possible for their direct and close collaboration with the textile industry and fashion brands, by promoting more awareness in their interlocutors in order to orient them towards the benefits of a rather reduced scale of application.

Given the potential of the technological material innovations illustrated, the limits must also be remarked: the costs of leather alternatives, which are currently equivalent to the luxury leather market; low tensile strength of the fruiting body leather and yarn; the pilot scale level of the majority of these processes.

If the theoretical premise supports the foundation of a new materialist vision for both professional interpreters and consumers, as well as the establishment of new materialities and new materialist technologies that are overall more beneficial for the planet – as demonstrated by the insights gathered so far – this paper contributes to new materialist discussions within both fashion and non-fashion studies on theoretical and practical levels. Overall, the study provides valuable data that should inspire interdisciplinarity and strengthen the foundation for future research to continue the concrete exploration of our world.

## FUNGAL FUTURES

In conclusion, all the three fungal matter typologies described, collectively demonstrate that we fungi represent not only a sustainable alternative to animal leather but also a conceptual revolution in the fashion industry, posing an interdisciplinary challenge. It is crucial for fashion designers and material developers to adopt a collaborative mindset, engaging with a wide range of professionals to effectively address our unique biological characteristics. This implies re-discovering and historicizing previous technologies to integrate them with contemporary innovations, framing and signifying them within the "material turn." Transitioning from animal and synthetic leather to fungal-derived materials requires a paradigm shift beyond mere aesthetic and functional considerations, embracing a systemic approach that values our ability to grow and regenerate sustainably. Only through comprehensive and clear dissemination, deep understanding and appreciation of our intrinsic properties, can we fully harness our innovative potential to seamlessly integrate into the fashion products of tomorrow, contributing to the creation of a fashion future that is ethically and ecologically responsible.

## CAPTIONS

[Fig. 01] Mycelium substrate preparation for liquid fermentation, Biotechnology Lab of the University of Borås. Credits of the author.

[Fig. 02] Mushroom foraging and peeling. Courtesy of Pangaia Grado Zero.

[Fig. 03] Life Materials' Muskin implementation tests using conventional tanning industry machinery. Courtesy of Pangaia Grado Zero.

[Fig. 04] Fungal filament shown by PhD Kanishka Wijayarathna, Biotechnology Lab of the University of Borås. Credits of the author.

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