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Materialities of 'Mushroom-Leather'

A Critical Appraisal of the Material Dimensions and Sustainability of Fungus-Based Alternatives to Leather for use in Fashion and Textiles

Abstract

The ever more apparent unsustainable and unethical effects of the garment industry have caused consumers to face the dilemma of reconciling their interest in consumption with acting responsibly. The use of new materials in production, for example garments made from fungi, offers one way for consumers to resolve this. Fungi are being imbued with almost mythical attributes as a beneficial organism with transformative powers in many narratives – including ones from the fashion industry. Products are being promoted as if they were already widely available. However, the available information is ambivalent and might raise some doubt as to the material's market readiness and/or its overall sustainable effect. For this paper, I will analyse the information economy, celebratory narratives and mushroom materials from experimental fungus-growing experiments. I will examine closely the range of materialities around the phenomenon of fungus 'leather'.

Keywords: bio-economy, mushroom-leather, mycelium, fungi, fashion, textiles, materiality, knowledge

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Introduction

Fashion provides exciting potential for many consumers, facilitating the exploration of aesthetics, materials and visuals and the investigation of socio-cultural positionings in the world. But there is another side of it that is exploitative, polluting and socially irresponsible. Furthermore, by its principle of making looks obsolete sooner or later after having once been *en vogue*, it can be described as a waste production machine (see, e.g. Nayak et al. 2021; Remy et al. 2016). At a time of growing awareness of the mess the fashion industry leaves in its wake, fashion enthusiasts are increasingly facing up to ethical questions and are keen to reconcile their consumption with the knowledge that the products they buy have been made in a responsible, sustainable manner and do not produce excess refuse (e.g. Gazzola et al. 2020).

Principally, fashion products are made from a broad range of materials classified as either 'synthetic' or 'natural' materials. Synthetic materials are mineral-oil-based materials, meaning they draw on a non-renewable resource and produce long-lasting waste when disposed of, due to their resistance to decay. 'Natural material' does not, in the first place, refer to a material's performance in terms of sustainability. It refers to a material that is based on organic substances and fibres as raw materials. They could even be compostable were they not routinely finished or mixed with mineral-oil-based materials or other non-bio-degradable matter. In scaled industries, they have, nonetheless, an exploitative effect both socially and environmentally and an unfavourable climate balance. Some natural materials are ethically questionable, if not downright cruel, like animal hide, which is made into leather. Leather – allowing for differences in quality – lends itself quite well for use in garments. It can easily be sewn and used in garment or accessory production; it is generally malleable while still being very durable. The issues causing concern have to do with a lack of animal welfare, CO2 output and the pollution caused by animal husbandry. Another point of concern is that leather is a processed artefact: conventional tanning is not only extremely polluting, but also leaves toxic residue in the material (Lofrano et al. 2013).

Given the numerous harmful impacts of conventional materials, one of the strategies for conscientious fashion consumers is to look to the invention of new materials (e.g. Oki 2021; Preuss 2017; van der Haak 2018; Morby 2016). They are not alone in hoping new solutions will emerge from laboratories and the (material) experiments done by scientists and engineers. Many feel a palpable sense of excitement that the fashion industry is on the cusp of addressing the above-mentioned issues, actively countering resource-draining and refuse-accumulation practices. In this article, I concentrate on the possible use of alternatives to conventional leather for fashion materials. One of the raw materials that is currently exciting the imagination of many and receiving quite positive discursive treatment (e.g. Garcia-Pardo 2016; Schwartzberg 2019; BBC Ideas 2022) is that of fungi. As an alternative to leather, garments made from mushrooms are thought to be a humane, environmentally friendly and easily re-growable alternative for providing an abundant supply of material: it is widely known in public discourse as 'mushroom leather'.

The generic description 'mushroom leather' is technically imprecise. I am still going to make use of it at times in this article, though, because of its instant recognisability and because it is already deeply rooted in the popular imagination. But the term is mainly imprecise because the word leather refers quite specifically only to products made from animal skins and hides (e.g. Encyclopaedia Britannica 2023). In fact, the CEO of one of the best-known enterprises in this field, Matthew L. Scullin of MycoWorks, has attempted to curb expectations by stressing that his company's product is not a substitute for leather, but rather a new material quite in its own right (e.g. Scullin, interviewed by Menkes 2022). The second inaccuracy lies in the term 'mushroom': mushroom-'leather' is used to refer to (at least[1]) two very distinct types of fungi-derived products. Only one of them is actually made from mushrooms – which are the fruiting part of fungi. This product is called *amadou*. The other material is made from mycelium – which is a network of filaments, the root-like part of fungi. Mushrooms are not used in this mycelium-based material at all. It is the latter product that several enterprises are investing in currently. The companies concerned seek – all differences aside – to pile into the same niche that leather occupies in the industry for garments and accessories. The media has provided an abundance of information on its development, which suggests a broader interest in and readiness of the public for such fungus-based products and an expectation that they will replace animal leather. The producing companies generate support and funding, with the bioeconomy in general receiving increasing financial and structural support (International Advisory Council on Global Bioeconomy 2020, 158–163). The materials industry is dynamic and of great social relevance. New types of materials are continuously being developed for new purposes as soon as the technology is available. Due to advances in technology and genetic engineering, the possibility of transforming or growing mushrooms into a leather-like material generally appears quite plausible. For example, throughout the 2010s 'the future of fashion' was

1 Other fungus materials do exist, for example some made from Kombucha (yeast and bacteria) (e.g. Grushkin 2015; Oiljala 2014) and other liquid-growing cultures (e.g. Sangosanya 2022). But they are not considered here. The focus is on fungi growing in solid organic matter as a substrate to ensure comparability with the mushroom-leather products, which mostly dominate the discourse around this phenomenon.

often being discussed in laboratory settings (e.g. Backlight 2019; Dworsky 2014; Goormaghtigh 2017; Fries 2013; *The Economist* 2018).

However, from the beginning my practical and tacit knowledge of textiles, clothes and clothes-making has conflicted with what I was learning about and was being presented with in this context. With qualifications in textile science and costume design, I am familiar with the particular qualities that materials for use in garments (textiles as well as leather) must be imbued with, furnishing them with the ability to withstand the extreme stresses of wear, tear and care while at the same time satisfying the requirement that they are relatively pliable and soft. I was curious to find out about how the new fungus materials could meet such demands. When delving into the field in more detail, I was taken aback by the lack of tangibility of the phenomenon. Three enterprises have been the focus of countless media representations and the broader discourse about using mushroom-'leather' for garments: MycoWorks, Bolt Threads (which produces the mycelium-'leather' Mylo) and MycoTech. I had contacted the producers hoping to acquire samples of the material. But, despite my repeated requests to MycoWorks and Bolt Threads, I received no reply. Only towards the end of my research phase did I manage to buy a sample from MycoTech (discussed below).

So, to assess the phenomenon, I was reliant on the information presented on the companies' websites (MycoWorks[A], n.d.; Mylo[A], n.d.; MycoTech[A], n.d.). The information available in videos, in articles and on the websites had an almost ephemeral quality to it – never leading to any concrete results, instead only sending me into endless clicking loops and confusing echo chambers and continuously exposing me to the same few visual representations of the materials. All insights were tightly controlled, with the computer-generated videos often being artists' impressions, which seem to make liberal use of their artistic license, videos with suggestive cuts, blurred photographs from very specific angles and ever-recurring images of, e.g. a Hermès bag from 2021 (MycoWorks[C] n.d.; Hahn 2021; Luxiders n.d.; *Excellence Magazine* n.d.; Live Kindly n.d.).

Based on the premise that the garment sector is particularly demanding with respect to materials, the article shows how the websites make the case for mushroom-'leather' as a suitable fashion material and questions such a representation. I thus analyse them systematically, with specific emphasis placed on information about production (and its alignment with sustainable standards), the materiality of the products (to evaluate their performance potential in fashion items) as well as the range of products and their performance. I also consulted scholarly articles on the subject, including those that discuss mycelium-'leather', mainly from the material science angle, to supplement the information made available about production and performance by the companies.

However, experience psychologist Friedrich Weltzien and communication researcher Martin Scholz (2016) write that it is not possible to understand materials purely from a theoretical standpoint. When implemented for use in designs, it is essential for the designers to familiarise themselves with the physical properties of a material (Weltzien & Scholz 2016, 11). To better understand the tangible material dimension of the mushroom-'leather' phenomenon, I also conducted my own empirical experiments, growing fungi in my own home, exploring their material qualities and measuring them against the textual pieces of information concerning their production, materiality and performance. This strategy constitutes a tentative exploration of the performances of fungi in a more tangible way. Based on the observations, I formulated questions regarding the potentials of fungi material for garments.[2]

To provide insights into the social importance of materials and their customisations, which steadily increases their range of uses and respective social lives, this article first briefly explores the history of progressive customisation of materials through implementation of chemical and technological treatment. The descriptions of the various stages of technological advancement and the dynamics produced by the introduction of synthetic materials in the garment industry are then used to analyse the various dimensions of materiality in this article.

Materials and their societal impact

Materials are an important building block of economic activity. To add value and render them usable for specific purposes, since pre-historic times even 'natural' materials have been subjected to – rigorous – processing to alter their properties (e.g. blending or heat/mechanical treatment). For example, animal skins have been tanned to stabilise the material and make it resistant to decay by changing its protein structures using either fat, plant-based, and mineral-based tanning since approximately 8.000 BCE (Barbe n.d.). But raw materials will retain some of their idiosyncratic attributes, which determine the qualities and appearance of any product made from them. In her 2015 article 'Materials – The Story of Use', the anthropologist Susanne Küchler (2015, 268–269) points to a flurry of increased public and economic interest in the use of materials in Europe in the late 19th century, when an influx

2 DIY mushroom growing has been extensively documented on the internet, and it would be interesting to compare the results. However, the main aim here is to examine the empirical evidence of mushrooms' materiality to better understand how the mycelium grows and how the material performs.

of new materials from around the globe provided the bases for new products and inspired new ways of building and producing. This interest was further fuelled by the discovery of a new way of mechanically manipulating the properties of one such material, natural caoutchouc. This example offered the first insight into the immense impact a material could have socially. It had found use in water-proofing clothing even in the 19th century – with a notable example being the British Mackintosh raincoat, produced since 1823. But it was chemical alteration, which permitted 'the properties of the product to be varied to suit circumstances' (Allen 1972, 35) and this delivered the material to increased use options and creative exploitation. The chemical alteration of materials had a pronounced social impact, because it freed designers and producers from certain constraints that natural materials impose in the production process. This led to a phenomenon that the art historian Petra Lange-Berndt refers to as the caoutchouc-shock. Engineers as well as artists felt the emerging power and potential of being in charge of the end product's form and effect (Lange-Berndt 2002).[3]

The next great social impact of materials was felt when plastics made from mineral oil became available in the middle of the 20th century. The advent of these synthetic materials changed the market and revolutionised the concept of production and design even more (Postrel 2020, 218). While plastics also still have some irreducible characteristics, it is possible to imbue them with a very broad range of properties and appearances and employ them for very diverse uses – subordinating materiality to ideas and purpose. Their advent liberated art and design even more from the constraints – even dominance – of natural materials and permitted hitherto unthinkable formings and shapings. Polyurethane is one early example of a synthetic material that was so soft and flexible that, from the 1930s onwards, it was used to produce sponges. It is also one of the raw materials from which synthetic leathers are made. In 2022, world production of polyurethane reached 25.78 million metric tons, while 'it is forecast that the global market volume of polyurethane will grow to 31.27 million tons in the year 2030' (Statista 2023). Durability is another of its qualities. This has become one of the principal problems concerning the production of synthetic materials that the world is faced with today: waste products that do not decompose (Blesin & Möhring 2016, 183–184).

In fashion, too, chemical fibres changed the market significantly. DuPont, the US manufacturer and financier of the development of Nylon envisaged its main use to be in women's stockings in the 1930s. As Postrel (2020, 221) notes: 'When the first four thousand pairs went on sale [in October 1939 in

3 Similar to the example of the transformation of travel by the subsequent invention of inflatable rubber tyres.

New York], they sold out immediately, and within two years nylon accounted for 30 percent of the market for women's hose.' Being cheap and mostly easy to care for and clean, chemical fibres became firmly established in fashion. However, they were not, writes the anthropologist Kaori O'Connor (2005), immediately met with inherent enthusiasm in the early 20th century. Chemical fibres were at best initially perceived to be a cheap alternative. So, this 'hot sell' was not achieved without a major effort by the producers and marketers in working to understand the market and imbue the raw materials and the commodities produced from them with positive meanings to create a cultural receptiveness or even a feeling of necessity for them. O'Connor remarks that 'the economics of new fibres, which carry extremely high development costs, are such that for a fibre to be successful it must go into mass production' (O'Connor 2005, 46). The need to scale is the reason why, writes O'Connor, this interdependence between 'sussing out' consumers' needs and wants, creating fibres with specific qualities and careful marketing has continued to be of central importance.

In the 21st century, the functionality of materials has been further diversified through engineering and technology. Research has led to the development of materials with new properties to address everyday challenges in a variety of fields, for instance in building practices, dangerous professions, medicine or sports. They are not necessarily brought to market but can exist only theoretically – with their production details and eventual qualities archived in databases (Küchler 2015, 274). In their use, design and idea precede the actual physical material, which is then only produced on demand. By providing materials in this conceptual form, with many materials only existing in these databases with their computed properties, this is in effect freeing materials from having to take physical form. They can remain virtual and this virtual form does not necessarily impede the political, economic and symbolic importance of their potential use. Rather, as a result 'the early twenty-first century is being defined by a new materials economy driven by a flood of engineered technological materials whose capacities offer far-reaching promises' (Küchler 2015, 271). The advanced materials market is expected to grow even more in the next few years. The materials may be marketed on websites, which Küchler calls 'honeytraps'. In this virtual space, materials can be made to perform completely without regard to any physical constraints or laws of likelihood (Weltzien & Scholz 2016, 9). But Küchler sees a strong dynamic behind new materials also being driven by global political interest: 'As a result, the early twenty-first century is being defined by a new materials economy driven by a flood of engineered technological materials whose capacities offer far-reaching promises' (2015, 271). She argues that this leads to immense over-production and a new materials bubble: 'On-the-ground research shows that a staggering percentage of materials invented and manufactured at great cost rail within the first five months to establish a secure market, often for social rather than scientific reasons' (Küchler 2015, 271). While O'Connor – with a view to materials in the field of fashion and textiles – states that there is now a public awareness of the effect of man-made fibres (O'Connor 2005), Küchler warns – given the enormous impact that materials have – that their social performance needs to be studied more intensively, particularly for those cases where they are not taken up by users after production precisely because they do not perform favourably. This leads to them ending up as landfill; so, after having been produced at high energy costs, in addition they will pollute the environment as waste. This point is acutely pertinent in the case of fashion, where the effect of materiality is felt acutely by the wearers (Woodward 2005).

The emerging 'bio-economy' sends a fresh impulse surging through the materials industry, attracting political interest and investment in research and development (Fehr 2021). The core definition of the bio-economy's aim is the 'production and utilization of biological resources to generate high-value biobased products', taking another step towards innovation and invention, with an 'increasing proximity to converging technologies, such as biotechnology, nanotechnology, information technologies, and digitalization' (International Advisory Council on Bioeconomy 2020, 153). With the aim of addressing the problem of waste, toxic production and the use of non-renewable, mineral-oil-based resources, it draws on conventional bio-substances, even waste products, as raw materials. 'Innovation' features large in paving the way for the bio-economy (Braun 2021), and it lends credibility to the general endeavour with reference to emerging technologies, through which raw materials can be imbued with new attributes and characteristics. It promises new materials in addition to natural materials that can be altered to become more malleable for specific human use. But the alteration goes beyond mechanical or chemical manipulation of the raw material; next-gen materials are modified in their make-up through engineering or bio-manipulation. The term next-gen materials refers to materials with less negative of an environmental impact because they are based on abundant renewable resources and manage to mimic established natural materials. The result are familiar substances, which seemingly can be made to perform in unexpected but not impossible seeming ways. This saves resources and, if not polluted by chemical substances, the resulting products should be able to be recycled without problems after use. Bio-based or bio-degradable materials are certainly expected to be part of the answer to 'guilt-free' consumption (Blesin & Möhring 2016, 185).

Mushroom-'leather': *Amadou* and mycelium

In the following section, I take a closer look at the phenomenon of mushroom-'leather' against the backdrop of the evolution of such materials and their increasing social impact. Some *amadou* products were on display on the *MS Wissenschaft* in 2021, an exhibition ship funded by the German Federal Ministry for Education and Science, a travelling exhibition dedicated to the bio-economy. The exhibition touted *amadou* as one of the natural materials with potential to transform the economy as a vegan 'leather' (*MS Wissenschaft* 2021). *Amadou* is a product of an old craft of retrieving a spongy material from specific mushrooms. It is practiced, for example, in Romania using the mushroom *Fomes fomentatis*.[4] The mushrooms grow on dead and dying trees and are common in Europe, North America and Asia (Müller et al. 2007). A soft and supple material that looks and feels very much like suede can be produced from the sponge. Despite the science-based background of the ship, the necessary information provided to visitors on the potential – and limitations – of the material was scarce (MS Wissenschaft 2021). Exhibitions are a genre that for the most do not allow to delve deeply into subject matters. But I also understand the concentration on the positive aspects of *amadou* as part of a perceptible general commitment to supporting an affirmative discourse around the potential of mushroom materials as a leather substitute, even on the part of the 'science boat', without probing or questioning it too much.

It can be said that *amadou*, while being 're-discovered' now in the search for alternatives to animal leather, is not new but is instead only a matter of looking back on a long-standing tradition. When placing it within the spectrum of materials laid out above, *amadou* is in fact a 'natural' material that has been manipulated to make it usable in specific ways by humans.[5] *Amadou*, however, has idiosyncratic qualities that incorruptibly determine the form, function and appearance of the product. So, even though *amadou* looks similar to suede and seems to hold great promise as a leather substitute when viewed superficially, there are two main obstacles. The *first* is that it does not perform in the same way and is not durable in the same way as leather. It is sensitive to exposure to water, even moisture and friction. This means that resulting products cannot be washed and that out-door products must be protected from the effects of weather with waterproofing finishes (ZVNDER). Due to its lack of durability, *amadou* is used mainly in smaller products or in

4 This type of material is also found in *Phellinus ellipsoideus*, which grows in forests in subtropical regions.

5 The harvested materials must be stored in plastic bags for at least three weeks to keep them moist and soft (Schaub 2009, 30). They are then 'created by finely slicing and boiling the fungal fruiting bodies in an alkaline bath before manual stretching to form sheets' (Jones et al. 2021, 12).

products that are assembled from smaller pieces and need to be reinforced with other, sturdier materials. This limitation almost seems a minor drawback compared to the second issue that takes *Fomes fomentatis* out of the race as a competitor for leather substitution: the mushroom needs quite particular conditions to thrive in and cannot be domesticated. It has its own dissemination and growing rate – and production is not scalable. As engineers and chemists Jones et al. (2021, 12) observe: 'The limited supply of these fruiting bodies in nature and the time-consuming manufacturing process limits scalability and industrial viability.' Anna Lowenhaupt Tsing (2015, 38) calls this effect of resistance 'anti-plantation' – with reference to systematic colonialist agriculture that was both demeaning and exploitative of all the entities subjected in the process. This fungus is harvested mainly in the historical beech forests in the northern mountains of Bukowina, in Romania, during the autumn season. The best *Fomes fomentatis* grow in forests at heights of 800 m, where harvesting takes several days in the season. They provide quality gainful occupation for mushroom hunters, who self-determinedly follow traditional practices that continue to go under the radar of any possible supervision or disciplining (Schaub 2009, 40). They have thus far resisted exploitative practices in the wake of greater utilisation of the fungus. But it is lamentable that the natural material does not lend itself to becoming part of the future of the fashion industry and does not provide a solution for more responsible consumption.[6] Its lack of scalability leaves it in the domain and hands of craftspeople resisting the gravity of the industry's maelstrom.

Mycelium-'leather'

The real, tangible existence and suede-like appearance of *amadou* material and its prominent display in settings like the bio-economy exhibition feeds into the concept of mushroom-'leather' and its performance. It is used to blend into the concept of the potential of another contender in the field, mycelium-'leather',[7] which is a very different product. It is marketed as a technology-based manipulation of the familiar make-up of a natural raw material into a next-gen material to ready it for a completely new field of use and make it

6 It should also be noted that all raw materials that are grown on a larger scale (which is not possible with tinder fungus) might require environmentally harmful monocultures.

7 For example, in a report by DW News on the production of mycelium-'leather', one of the respondents, a scientist from the Fraunhofer Institute (see below), produced a piece of *amadou* and commented on its qualities. The report edits this segment into the clip just after having dealt with the same person explaining the production process of mycelium-'leather' without properly differentiating between the two entities (DW News 2020). As I will explain in more detail below, this part of the report was cut from the video clip in the current version.

perform in new ways. The raw material in this case consists of the 'root'-like part of the fungus, which is called mycelium. It is a birous material (made of chitinous polymers), which grows in the soil and/or organic material. The mycelium used to produce mushroom-'leather' grows mostly on woodchips as a substrate. When it grows profusely, is not interlaced with substrate or other matter and before it is dried, mycelium is a fluffy mat of interwoven strands and has the appearance of candy floss. What makes it particularly interesting for environmental reasons is that it is 'a biological organism to do all of your manufacturing for you, so there is no real energy requirement' (Elbein 2020). It would be very quick to grow and could be composted (if it remains purely organic). Production involves scant CO2 release (hardly any heat and no light are needed); in fact, fungi store more CO2 than the production would set off.[8] Some bioengineering is implemented to control the mycelium's growing process (MycoWorks[D] nd.). Jones et al. (2021, 14) argue: 'In addition to being more environmentally sustainable to produce than leather and its synthetic alternatives, as they do not rely on livestock farming or the use of fossil resources, pure fungi-biomass-based "leather" substitutes are also biodegradable at the end of their service life and cheap to manufacture.' Another interdisciplinary article states that mycelium 'has become a highlight in biomaterial engineering, owing to its zero pollution and renewability during the formation and treatment processes' (Raman et al. 2022). So, knowledge of this product from the perspective of the natural and material sciences will help researchers further evaluate its production as part of an environmentally sound process. This could make the material an innovative bio-economy contender: cheap, bountiful, cruelty free and made to perform at will.

Producers are hoping to replace a variety of alternatives to leather already on the market made from 'synthetic' materials, like polyvinyl chloride (PVC) and polyurethane (PU). Like other synthetic materials, they can be cheap to produce; they are durable and do not have to be tanned, like conventional leather, and they have the advantage of not being produced using processes that are necessarily cruel to animals. For production, compared with leather they seem to perform quite well by having a better climate balance with respect to CO2 emissions and water use (Jones, Gandia, John, and Bismarck 2021, 10).[9] However, they have a number of drawbacks. They generally do not perform as well physiologically with a human body, they might not be as durable, they

8 However, sterilising the substrates – which can be made up of waste products – through pasteurisation and suitable surroundings is necessary, and moderate heat might speed up the growing process depending on the fungus.

9 Some types of leather made from animal hides can be by-products of the meat industry. While the CO2 content is still high, in this case they do not release additional gas into the atmosphere.

might use up finite resources, they can be toxic during production and they leave toxic waste after falling into disuse or else can leak micro-plastics from the moment of their production (e.g. Oluwaseun Adetunji 2021; Commission of the European Communities 2000). Some other leather substitutes are partially made from biological waste products, like Piñatex, which is made from the fibres of pineapple leaves and use polylactic acid and 'water-based' polyurethane as a resin (Piñatex n.d.). This process serves to make them hydrophobic, binds the particles or fibres together, and gives them a 'leather-like' appearance and feel. So, they reduce waste but still need some synthetic additives. This makes them a mixture of natural and synthetic materials.

Representation of the materiality of mycelium-'leather'

Mycelium-'leather', by contrast, is generally marketed based solely on its biomass qualities. Marketers claim it has the potential to become a cruelty free, sustainable, natural and ethical luxurious substitute. The projections are generating economic interest. The think-tank Material Innovation Initiative states that, in the last ten years, $3 billion has been invested the field as a result (Material Innovation Initiative 2023). MycoWorks has generated $125 million in financing in 2021 from Prime Movers Lab, SK Networks, Mirabaud Lifestyle Impact & Innovation Fund, DCVC Bio, Novo Holdings and several other strategic customers and investors (Waltz 2022), followed by an estimated $63 million in October of 2022 (Waltz 2022, 15). In an opinion piece, Scullin (2023) writes that such strong financial interest has been, 'driving excitement around next-generation materials like mushroom leather [and others]'.

In the following section, I trace the materiality of mycelium-based mushroom-'leather' as it is described and marketed by the producers MycoWorks, Bolt Threads and MycoTech. The information, which shapes the material essence of mushroom 'leather' in its various forms, presents itself like pieces of a puzzle, or pieces of data. MycoWorks, which is the most prolific of the three firms, was founded by artists Philip Ross and Sophia Wang in 2013 (Hall 2021). One article about the company explains its mission as follows: 'Based on their strong financial structure and high-quality personnel, these companies collaborate with leading luxury companies, including Hermès and Mercedes-Benz, to produce basic raw leather, personal luxury items, and car interior materials' (Raman et al. 2022). But product descriptions remain opaque. They are well designed and appealing but use vague marketing language. The mysteriousness can – in part – be explained by the firm protecting production secrets in a niche market that is both promising and expected to become extremely profitable for ethical and responsible fashion. However, even other articles refer to and reproduce information given by the producers themselves to rate the products. For example, the biotech journalist Emily Waltz describes the production process as follows:

> MycoWorks […] grows the fungus from the species G. lucidum in trays of sawdust the size of half of a cow hide. Researchers coax the fungus to grow and branch into threadlike filamentous structures called hyphae (collectively termed mycelium) using proprietary tricks that involve controlling temperature, humidity, carbon dioxide levels and other aspects of the fungus's environment. The fungus colonizes the trays, resulting in a material that, through an undisclosed proprietary procedure, looks and feels like leather, according to the company. (Waltz 2022)

The mats of interwoven mycelium are then harvested and treated – in a tanning process – to take on qualities due to which the product is likened to leather. In her overview of the new uses of biomaterials, Jane Wood refers to MycoWorks in the following uncritical manner, her sole reference being the company's own website:

> The company uses the growing process of mycelium to bind with organic matter, thus creating a 'solid' textile, which is more akin to leather in appearance, rather than a traditional knit or woven fabric. The resulting material is flexible, durable, can be dyed easily and with natural dyestuffs, and has a degree of water repellency. (Wood 2019, 5)

Jones et al. (2021) actually explain in detail how the fungal sheets are grown:

> [S]olid-state fermentation typically utilizes a bed of forestry by-products, such as sawdust, high concentrations of carbon dioxide and controlled humidity and temperature to force the aerial hyphae to grow outwards in search of oxygen, avoiding stipe, cap and spore production. The continuous mat formed on top of the particle bed is then dehydrated to render the fungus inert, chemically treated to improve material properties, compressed to a desired thickness and imprinted with a selected pattern. (Jones et al. 2021, 11)

The authors go on to explain the chemical and technical processes that MycoWorks implements to make the material more leather-like. For their performance analysis, Jones et al. (2021, 13–14) also base their analysis on information provided by the company. Articles on the sustainability value of such products refer only to the companies' claims about the production process, taking them at face value, thereby supplying knowledge in an echo chamber. Thus, the materiality of mushroom-'leather' is developing momentum purely in a discursive format. The material may have physical effects 'in the empirical world', but it exists to the reader and to some of the observers only as a representation without being grounded in concrete experience.

Mushroom-growing experiments for empirical insights on the materiality of fungi

All fungi are basically made of the same material building blocks: a chitin-glucan complex, a polysaccharide. This type of structure is unique to fungi and sets them apart from other organisms (plants and animals).[10] The specific compositional relations of the chitin and glucan in the complex can vary and, at times, instead of chitin the cell walls can contain chitosan, which has similar properties (Freitas et al. 2015). As Abo Elsoud and El Kady (2019, 6) note: 'Generally, the fungal cell walls are composed of chitin, chitosan, neutral polysaccharides, and glycoproteins in addition to minor amounts of polyuronides, galactosamine polymers, lipids, and melanin.' (For more discussion, see also Freitas et al., 2015, 2.) Chitin is a 'rigid polymer that is synthesized at the cell wall of the mycelium in order to protect its filaments by internal osmotic pressure, external humidity and other chemical and physical challenges' (Haneef et al. 2017, 8). It is the building block for all the parts of the fungus, including mycelium and mushrooms. Due to the unique and unifying make-up of the fungi cell walls, my basic assumption is that the materiality of the fungi that I am using and that of the fungi used for growing mycelium leather are comparable at a basic level, even though they do have different tensile strengths (Jones et al. 2021, 13).

All of the fungi utilised for mycelium-'leather' are filamentous fungi.[11] Mycoworks uses the Reishi (*Ganoderma lucidum)* for its *Reishi* product (Waltz & Nature Biotechnology 2022). Bolt Threads does not specify, which exact fungi it uses to produce the product Mylo. However, an oyster mushroom (*Pleurotus ostreatus*) is shown in the heading picture of a website referring to them (Objcts.io n.d.), and oyster mushrooms are a common fungus species used for growing mycelium (Varkki 2024). In my experiments, I also grew commercially available, edible mushrooms: Enoki (*Flammulina filiformis*), Pioppino (*Cyclocybe aegerita*), Lion's mane mushroom (*Hericium erinaceus*) and Button mushrooms (*Agaricus bisporus*). The first three were acquired as spores in a block of wood chips covered in transparent plastic on 15 January 2023. They

10 But some plants do contain glucan, and some invertebrates have chitin in their exoskeleton.

11 Fungi are either filamentous fungi or yeasts. Yeasts grow by budding. Mycelium consists of fungal filaments (hyphae) that have grown into a 'complex network' (Powers-Fletcher et al. 2016).

naturally grow on dead[12] wood in forests. To grow them for this study, I followed the provider's instructions. Wood chips serve as substrate (the habitat) for the fungi when they have developed from spores and provide the organic matter for them to feed on. The plastic covers regulate the humidity of the woodchip block. They needed to be slit carefully to allow the mushrooms to grow but not dry out. Extra humidity had to be provided regularly by spraying the ensembles. The necessary temperatures varied from 7–18 degrees Celsius (Enoki) to 20–25 degrees Celsius (Pioppino) and 10–20 degrees Celsius (Lion's mane). By the end of January, all three had grown mycelium inside of the substrate, and mushrooms sprouted from all sides of the block. It was possible to harvest the mushrooms. However, the remnants of the stems in the block developed mould quite quickly in the warm and humid conditions. So, it served as a breeding ground for other fungi (and possibly other organisms). By this time, the substrate had been diminished due to the decomposing action of the mycelium (it has served the fungi as food). The mycelium was visible as white webs interwoven with it, but never outside of it, or on the outside of the plastic cover.

The button mushrooms required a slightly different set up. The woodchip substrate infused with the fungus spores was covered by a 5 cm thick layer of moist soil in a transparent plastic bag placed inside a cardboard box. The temperature during the time when the spores were developing into mycelium had to be 21 degrees Celsius. Humidity had to be ensured by covering the ensemble with plastic covers, and the box was closed to exclude all light. I added a cotton t-shirt to one sample, which I placed on top of the soil, immersed partially, to see how the fungus would interact with the textile material. I grew another sample without using the t-shirt as a control sample. Once mycelium was visible on the surface of the soil (after 15 days), the temperatures had to be lowered to 15–18 degrees Celsius. Mushrooms started growing after another 20 days. I grew two boxes of button mushrooms. The t-shirt that had been placed in the box had decomposed wherever it had been immersed in the soil. Pigments in the colour of the t-shirt were surfacing in other parts of the box, on top of the soil. The mushrooms kept growing and ultimately had to be harvested. By the end of March (after two and a half month), green mould had started showing on the surface the soil between the button mushrooms. Samples of mycelium and mushrooms from the four types of fungi were dried to examine the changes in the material's properties. The samples hardened to a woodiness and changed from a malleable state to exhibiting more of a crispy brittleness. They could not be bent or changed from the shape they had dried

12 Lion's mane mushroom (*Hericium erinaceus*) and oyster mushroom (*Pleurotus ostreatus*) can also grow on living trees.

into and would snap if manipulated. One larger mushroom that had not been laid out to dry carefully or turned over to let the air circulate around it (rather, its cap was in full contact with the surface) developed mould.

Before I start relating my observations to the data provided by the websites, videos and articles, I need to highlight the obvious limitations of such an experiment. The growing settings and the available technology are unequal to those of the companies producing mycelium-'leather'. Due to the opaqueness of the companies' processes, no comparability can be assumed. However, the observations do serve as a foundation for formulating questions regarding the performance or basic suitability of fungi raw materials for garments and also their representation on the websites and in the media in digital space.

Observations and resulting questions

First observation

During the course of the mushroom-growing experiments, I was able to observe that the mycelium decomposed not only the substrate but also the cotton material of the cotton t-shirt that I had placed in the box and partially submerged in the soil. It had completely metabolised those parts of it that had been immersed in the soil of the growing box. Only small bits of the dye pigment appeared on the surface of the soil throughout the box, probably discharged due to its un-digestibility. But the mycelium had treated the cotton (which, like the wood chips at the bottom of the box it was meant to feed on, is made of cellulose) as a substrate.

MycoWorks states on its website that it produces three different mycelium-based 'leather' products: pure mycelium, mycelium grown into a textile made of cotton and mycelium grown into a textile made of polyester (MycoWorks[E] n.d.; see also, e.g. Williams 2022). In early 2024, the vice president in charge of sales, Fred Martel, was quoted as saying that the company was considering the option of making the mycelium grow into a woven cotton material. He has stated that one of their products, 'Reishi', can be grown into a sheet of cotton to make a whole new material that rivals animal leather (Teisseire 2024). At the time of first reading this in 2022, the idea had made sense to me, because the textile material could potentially enhance the flexibility and durability of the product.[13] But after observing the digesting process firsthand, it now seems questionable that this very simple metabolising process, at the very centre of mycelium's growth action, can be prevented from occurring,

13 Many synthetic 'leathers' are reinforced with textile backings to increase their durability.

even through the use of technology or bio-engineering.[14] This raises the question: If mycelium treats cellulose textile materials as a substrate and cotton textile materials also as cellulose materials, how then can cotton be integrated with the mycelium during the growth process to 'strengthen' the product?

Second observation

In the experiment, the matter in the *Agaricus bisporus* boxes was made up of substrate, soil and the growing fungus (mycelium and mushrooms). Since they had to be kept moist and at room temperature, eventually the contents of the boxes (both with and without the t-shirt) developed mould, as was to be expected. As natural materials, fungi are susceptible to infection via pathogens. MycoWorks CEO Scullin stresses that the company goes to great lengths to ensure that the facilities and the growing process are kept free of contamination. The fashion blogger Suzy Menkes asked the CEO Matthew L. Scullin in 2022 why, during a visit to MycoWorks, she was not allowed to view the production site, which was carefully guarded. Scullin's response was that the site must be kept sterile (Menkes 2022), so that during production, when the mycelium is still fresh, the controlled laboratory environment will prevent pathogens from taking hold.

I also observed that mould started growing on mushrooms that had not been properly dried. In their dried form, the mycelium sheets are not inducive to attracting microorganisms as hosts. But one of the studies evaluating the performance of mycelium-'leather' identified a problem with mycelium-'leather' soaking up and retaining moisture (Raman et al. 2022). This would make the material vulnerable to decay even at later stages of use. Jones et al. (2021) noted that the natural decomposing effect of mycelium is counteracted by a chemical treatment of the material after it has been grown into a sheet: 'Initially, the precursor tissue may be treated with lipids, moisturizing or hydrating agents, such as glycerol or sorbitol, to increase its water content, and sectioned. The tissue is then immersed in, vacuum infused or injected with sodium hydroxide, acetic acid or alcohol, such as isopropanol, ethanol or methanol, for periods potentially ranging from five seconds to six months.' (Jones et al. 2021, 11–12) The solution the material is treated with removes tissue from the mycelium and denatures the remaining proteins to protect it from susceptibility (Kaplan-Bie 2018). MycoWorks and Bolt Threads make mention of a tanning process for mycelium-'leather'. MycoWorks stresses that it is a chrome-free tanning process (MycoWorks[B] n.d.). Bolt Threads states that it is using a 'gold-rated tannery' by the Leather Working Group (LWG) (Mylo[D]

14 I have asked for more information about this process in several comments to posts by MycoWorks on LinkedIn and Instagram, but I have not received responses.

n.d.).[15] This means that this new material does not provide a tan-free alternative to leather. Neither is it the compostable product that Jones et al. tout it as (see above).

The observation points to still another potential problem with this natural material. If fungi substances are prone to retaining moisture, then the issue is particularly pertinent for the everyday wearing of clothes made from this material. They will invariably be exposed to the body's perspiration and/or humidity from weather conditions.[16] The addition of a material like polyurethane – as will be discussed in more detail below – could make the product hydrophobic and prevent it from absorbing moisture. However, this raises the question whether mycelium-'leather' can count unreservedly as a sustainable material if it has to be treated, de-natured and even have synthetic materials added to it.

Third observation

The mycelium in my experiment became brittle once it had dried – it did not retain its flexibility or durability. As mentioned above, comparability is limited, because MycoWorks and Bolt Threads did not use the same fungi as I have.[17] Jones et al. (2021) have suggested that the mycelium used in the materials being marketed are engineered or genetically altered without elaborating on how exactly that could be done. Researchers also state that, because mycelium is an organic living entity dependent on nutrients, moisture and the right environmental conditions, the composite they grow in is significant for its resulting performance. But, as stated above, all fungi have in common the fact that they contain chitin. Chitin has been investigated for use in items demanding high textile quality. For example, health and medical researcher Pierre Layrolle has examined chitin as a possible raw material for sutures. But his findings are that the potential is limited:

Although the apparent potential of chitin and chitosan derivatives in the preparation of sutures have long been recognized, there is still no commercial production of chitin-based absorbable suture materials because of insufficient

15 The tannery's website does not mention Mylo or any other fungus-'leather' product (Leather Working Group n.d.). This is surprising in the sense that the tanning procedure for mycelium would be quite different to that used to tan animal hide and would have warranted mention in the company's portfolio.

16 Mylo's life cycle assessment simply addresses the ecological impact but not the use performance of the product (MyloC).

17 The websites for the most part do not specify what fungi are used for this type of material. Raman et al. (2022), though, provide details on the fungi that they used to evaluate the performance of mushroom-'leather'.

elasticity of chitin threads and certain limitations of their processability into the fibre form. (Layrolle 2011, 230)

This same lack of elasticity has been highlighted in articles studying the qualities of mycelium-'leather', too. While Raman et al. (2022) are generally positive about the *potential* of mycelium-'leather', they are more hesitant about touting the performance of the product. The authors point to a lack of flexibility and a lack of resistance to friction, which will have to be addressed (Raman et al. 2022). In another article, Jones et al. (2021, 11–12) note that manufacturers could compensate for this lack of elasticity by lubricating the material to ensure a leather-like performance through physical and chemical processing, thus counteracting its potential brittleness. However, others have stressed that 'plasticizers should be natural and biodegradable with low toxicity and good compatibility with mycelial biomaterials' (Raman et al. 2022).

As already noted above, I had contacted MycoWorks and Bolt Threads several times through their websites (using contact interfaces mainly directed at buyers), but they did not respond to any of my many requests for information, nor was I able to acquire any samples to enable me to evaluate the attributes, quality or performance of the material.[18] However, MycoTech has recently sent me two samples.[19] They turned out to be very dense, rigid sheets of material, which do not evoke any associations of leather – or suitability for use in garments. Both are mounted on a very thin woven textile material. (A closer description of the samples follows below.) Even though MycoTech's samples do not allow any conclusions about the other products discussed in this article, this example underscores the general issue of a lack of flexibility of dried mycelium mentioned above. This raises the question: If Mycelium lacks flexibility and becomes brittle when dried, and if it requires significant processing to alter its make-up, then what qualifies it as a raw material in garment production in the first place?

Fourth observation

The mycelium in my experiments lived and grew inside the wood-chip blocks and never began to grow on sheets outside of the plastic sheets. The mycelium became visible as a white web on the surface of the substrate, but it was

18 Some products seem to be on sale through the website, but I cannot find any way to purchase them myself through the websites or with the google shopping filter. The websites repeatedly feature carefully chosen and controlled images, artists impressions and short videos, but there is a conspicuous lack of samples of the material to really understand or know what it can do

19 One of the samples was black and the other ochre-coloured with speckles – a 'mushroom' colour. Mycelium-'leathers' on display are often tinted in the latter, as if the colour occurred naturally, or black. Mycelium is naturally white, however.

deeply intertwined with the material. It built its web deep inside the sawdust within the blocks. The mycelium growing out of the substrate block did not at any point form tufts of fluff on top of the block or grow into a sheet on the outside of the plastic wrap.

This conflicts with a video clip from the German news outlet DW News on the Indonesian company MycoTech, which (at the time of filming) operates from a small warehouse (DW News, 2020). The clip shows shelves with blocks of substrate wrapped in transparent plastic, with mushrooms growing out of them, each with a bit of white fluff – with the appearance of wispy textile fibres – on top (DW, min. 0:12–0:18). The narrator, in describing the production process at MycoWorks, says ‘on the outside of these sawdust blocks they produce tightly woven mycelium, which can be harvested within a few days’ (DW, min 1:55–2:01). The visuals show the sawdust blocks, and the camera then turns to workers manipulating and scraping 30 x 30 cm squares of floppy, moist, beige-coloured material and hanging them up to dry. This imagery suggests that the mushroom-‘leather’ had first been peeled outside of the blocks and that it grows readily into the featured sheets, which would make it a natural material not requiring any manipulation and added value at all.

When I first accessed the DW News video on MycoTech in June 2023, it featured a young scientist from the German Fraunhofer Institute relaying that he was involved in the process of producing fungus ‘leather’ and offering his view on the issue. He spoke quite positively about the process and served as the scientific source of credibility in the report (wearing a white lab coat). The sample that he had shown to the camera in the clip had seemed quite rigid. This indication of the material’s performance roused my interest. In June 2023, I contacted him – and he actually responded, which surprised me after the consistent ghosting I had experienced when attempting to contact the companies. However, when I asked if I could study a sample of his fungus material, he said it was not possible. After his affirmative statements and the positive outlook provided in the report, the response surprised me even more. Again, I was not able to acquire any samples. The scientist explained to me in more detail his viewpoint, stating that the science and technology had not progressed far enough yet to produce mushroom-‘leather’ at all. Rather, he wrote in the email that the product was still in the developmental stage. He had received many requests regarding this issue and explained to me that it was not worthwhile to send samples because it would require a great deal of paperwork and prior agreements.[20] His appearance in the video clip has since been removed from the report (without any mention of the change in the pro-

20 The email exchange has been archived by the author.

duction details) (DW News 2020). This underlines the ephemeral quality of online information and the ease with which it can be manipulated. This raises questions about the relationship between the mediatised representations of the materials and the analogue materials that they refer to. What limits the performance potential of a material that exists in digital space?

The materialities of mycelium-‘leather’

For a long time, the producers of these types of alternative mushroom-‘leathers’ have claimed that they are free of mineral-oil-based materials. Bolt Threads has, however, since had to admit that they are indeed adding ‘water-based polyurethane’ to its product Mylo. This means that their mycelium-‘leather’ does not qualify as a next-gen material – a natural material with enhanced qualities through engineering. It is, instead, a natural material mixed with ‘synthetic’ materials. This addition is known to make natural raw materials hydrophobic and add flexibility and strength.[21] Following this shift in marketing, the website now states that the company adds ‘water-based polyurethane’ to its product to imbue it with additional required qualities. Some voices claim that using chemical fibres or raw materials would still be more favourable for the environment than using animal hide (e.g. Vacano et al. 2021). After having entered into partnerships with Stella McCartney, Adidas, Lululemon and others, the company has, however, currently halted production due to ‘inflation and waning funding opportunities’ (Chan & Webb 2023).[22]

I have carried out a burning behaviour test on the sample I had received from MycoTech being counseled by the textile sustainability expert and chemist Norbert Henzel in October 2023: the material burned vigorously, emitting small sparks and producing thick grey smoke with a bitter, pungent odour. This behaviour could point to the fact that at least part of the material is of synthetic origin. A small remainder of light ash at the tip of the charred part testifies to its organic components, suggesting that the sample is a mixture of natural and synthetic materials. By comparison, I was not able to light my own dried mycelium sample, nor could it burn by on its own. When immediately exposed to a flame, it produced a slightly bitter smell, some light smoke and a whisp of light grey ash, which indicates the organic make-up of the substance. Henzel makes sure to point out that a definitive analysis determining the composition of this material would need to be carried out in a laboratory test.

21 One customer stated that they had only found out about this synthetic component from the factory making the products made with Mylo’s leather substitute (Tonti 2023).

22 Its website, however, continues to promote the product without making any reference to the difficulties faced in producing it (MyloA), which seems to suggest that it is still poised to play a part in the market.

Intractable natural material

So far, most of the products that the companies advertise on their websites are accessories, like purses and bags or jewellery. These are often made up of smaller pieces of material and a possible lack of flexibility is not as striking. However, Stella McCartney designed a whole outfit made with Bolt Threads's mycelium-'leather' Mylo in 2021. It is a design implementing smaller pieces of the product; they are jointed by a textile jersey material. This design has been widely used to support the narrative of mushroom-'leather' having entered the market successfully. However, it has never gone into production. The label's statement on its website reads: 'We used Mylo™ to create two garments – a black bustier top and utilitarian trousers – that are not for sale but do embody the potential of this next-generation material and pave the way for future commercial offerings' (Stella McCartney[A]). The use of Bolt Threads's mycelium-'leather' for small handbags in 2022 proved more fruitful. They are readily available for sale (Stella McCartney[B]). MycoTech's mycelium-'leather' has been used in a collection by the label Apakabar in 2022 (MycoTech[B]). Again, only smaller pieces of the mycelium product have found use. In this collection they were sewn onto textile pieces (woven or jersey). The label's website shows a single piece, a blouson jacket, which seems to be made mainly from mycelium material. It consists of patch-worked smaller pieces that are – as becomes evident on closer inspection – reinforced by a textile material on their left side (Apakabar Atelier). Beyond this, MycoTech is mainly offering small accessories (which are often thick and inflexible), but it has diversified and now lists home furnishings in its portfolio as well. MycoWorks has recently cooperated with General Motors to provide material for the interior of a luxury Cadillac called SOLLEI (2024). The headlines and various pictures posted to mark this project do not do much to prevent the impression that the collaboration encompasses the car's whole lush interior upholstery. One of the posts starts off evocatively: 'Imagine one day being able to grow material to the exact size of a steering wheel or dashboard, reducing offcuts and speeding up supply chains. Fine Mycelium™ materials are a new category of their own.' (MycoWorks[F] 2024). The attentive reader learns that mushroom-'leather' is used for the car's charging mat cover and the door pocket linings only. Of course, these are areas, in which the material does not have to endure excessive stress. The prevalent use of small pieces in all these examples, in places where they are not subjected to wear and tear or which are joined by textile jersey and/or reinforced by textile materials on their left side, points very strongly to an, as of yet, unsurmountable lack of flexibility and stability of the product itself.

However, as pointed out above, Scullin has already promoted MycoWorks' product as a material in its own right while dampening down expectations of it becoming a full-scale replacement for leather (Menkes, 13:30–13:57 min.). It has recently appeared in an interesting collection (to which I also only have mediatised access): Deadwood Studios has created a line of products from Fine Mycelium (Deadwood 2023).[23] The designer team is making the stiffness of the material readily apparent in the pictures – which is probably the signature component of the in-submissible part of the mycelium – as the dominant look. A video presentation of the collection provides viewers with only two short glimpses of a model wearing one of the designs (Deadwood Studios, 2023, min. 2:34–2:41 & 4:37–4:48). It is an ochre-coloured belted long-jacket, which is quite striking in the otherwise more dust-grey-tinted collection, with its somewhat apocalyptic theme. This sensitivity to the idiosyncrasy of the material might indeed be the way forward to understanding what it can do in fashion. It is a tribute to the material as an inspiration to the designer (Spellmeyer 2016), and an acknowledgement of it being something other than a leather substitute and that 'fashion companies have to understand how to offer products and experiences that customers will perceive as unique' (Rath & Bay 2015). So, in this scenario, and despite the generated expectations and the economic interest in the material, mycelium-'leather' does not present itself as a next-gen material that can be bent to human will, ingenuity and purpose through the implementation of knowledge and technology. Rather than possibly setting off a caoutchouc-chock-type aftermath of increased productivity and societal advancement, mushroom-'leather' has producers and designers bent to its own idiosyncratic qualities. To fully develop into a fashion material, however, it will not only have to address material and physiological challenges. It will also have to be able to be adapted to respond to fashion's demand to aesthetic innovation fluidly.

Conclusion

The phenomenon of mushroom-'leather' presents itself in a broad range of materialities. *Amadou* is made from a natural material that is distinctive and

23 Interestingly, MycoWorks' website features a link to Deadwoods SS24 Runway show. MycoWorks is not mentioned by name in the accompanying text at all. A link from the MycoWorks website to the new collection of Deadwood products leads to the show, in which neither MycoWorks nor its products are mentioned. Rather, the blurb mentions cactus 'leather': 'The core idea was simple: Garments and accessories made from materials that otherwise would have gone to waste. Pioneering the use of upcycled leather and vegan cactus "leather", continuously experimenting with new material compositions, and always encouraging carefully considered clothing – Deadwood is preparing for an unexpected tomorrow' (Deadwood Studios 2023).

intractable. It is not scalable, but instead largely re-enforces specific practices evolving around it, and it can only be used in idiosyncratic products. Some of the properties of fungi will surely lend themselves to technological and engineered alterations and become infused with alternative attributes. If it were possible to completely overhaul the conventional attributes and bolster the required ones sufficiently, then such a move could be the starting point for upcycling waste products, harnessing abundant non-toxic vegetable resources and creating items that can be composted at the end of their life cycle, but my observations of the physical material suggest that the range of possibilities are not limitless in this respect. As next generation materials, manufacturers have praised new bio-materials like fungus-'leather' for bringing new options to the table, which can address urgent sustainability and responsibility issues in the fashion system. Material and natural science studies seem to support the feasibility to a certain extent. Its actual material impact is not yet easy to predict, though, and none of the studies go so far as to vouch for their usefulness in fashion products. Mycelium-'leather' has not been fully realised from a physical standpoint, but it has been produced in part in a mediated way – with the potential to materialise completely in the future. It has – this is becoming evident – gathered great momentum as a material, though it currently exists mainly in digital form without having been subjected to the forces of friction. This example shows that a material can be very powerful and socially effective as an idea, but as an immanent physical material it still might not perform up to the imagined standard and thereby loses some of its compulsive force.

The fashion sector places extreme demands on its materials, not only regarding their functionality (being able to withstand the wear and tear of strain and also care practices) but also their aesthetic effects and – increasingly of late – their sustainability and environmental responsibility. Fashion can thus accentuate any shortcomings of the materials in this respect (when they might be very functional in other fields of implementation). The successful use of mushroom-'leather' in fashion has proven challenging because the product – while of 'natural origin' – has not been devised, or so I conclude, by building on its natural strengths (even though marketers give such an impression by stressing that the mycelium can grow into entangled networks and suggesting that these networks serve as the durable basis of the mushroom-'leather'). Instead, the mycelium must be coaxed, possibly genetically modified or chemically altered, to even broadly be able to serve as a raw material. So, despite all the technological progress and modifications made to fungi, which numerous articles promote, it does not seem to be easy to make fungi perform at will in the realm of fashion. Another issue is that after having been subjected to the various manipulating processes, it is questionable whether mycelium-‘leather’ could still be disposed of responsibly after use or whether it would become another product that does not decompose.

The article has highlighted references made to the economic possibilities and the invention of materials in the realm of the imaginary beyond any tangible materiality. The websites and the information made available constantly change before one’s eyes, even during the research done here. It is puzzling why mycelium – which turns wooden and brittle when dried – should be used as a raw material substitute for leather – beyond the use of its evocative effect. Rather, mycelium-‘leather’ apparently performs in a similar manner as the virtual materials described above: they exist mainly in a dimension beyond their own materiality. As Küchler (2015) also writes, even in this ideal state they still add to the value of the sizable materials industry. They are presented in their material state, but the qualities of the materials and projections of their future uses are largely mediated and outlined on the companies’ websites, which could be characterised as honeytraps, and in echo chambers in other media. As such, the use of sustainable materials develops its own discursive momentum, with a large symbolic dimension, due to their potential future use in fashion. The list of such materials can easily be multiplied and marketed, and it has commercial potential – trying to attract some of the larger investments made in the sector. Since it is expensive to produce innovative materials, they need constant marketing – as was the case for the newly marketed synthetic fibres mentioned above. Companies have been able to generate a great deal of interest and also much funding for their research, though with relatively few products to show for it. There is an urgent need to address exploitative and cruel production practices, including the use of animal hides.[24] It can be concluded that the market *is* ready for this idea. Maybe that explains the lack of demand for empirical knowledge in this field. For the future of fashion, however, there needs to be more certainty. The effort to create mushroom-‘leather’ and the ideal already being outlined does, however, give fashion enthusiasts reason to hope that consumption practices can meet the ideal of a sustainable product.

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24 It has been suggested that one of the problems might be scaling production, too (Pucker 2023).

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SOURCES

Apakabar Atelier. Wowow. Accessed June 07, 2024. https://www.apakabaratelier.com/shopping/wowow.

Abo Elsoud, Mostafa M., and E. M. El Kady. 2019. "Current Trends in Fungal Biosynthesis of Chitin and Chitosan." *Bulletin of the National Research Centre*, 43–59. Accessed October 30, 2023. https://bnrc.springeropen.com/articles/10.1186/s42269-019-0105-y.

Barbe, Josephine. Nd. The History of Leather Tanning.

Maharam.com. Accessed June 19, 2024. https://www.maharam.com/stories/barbe_the-history-of-leather-tanning

Backlight. 2019. "Where the Future of Fashion Is Headed." *VPRO Documentary*. Accessed November 04, 2023. https://www.youtube.com/watch?v=DUFjz4GoIEw&ab_channel=vprodocumentary.

BBC Ideas. 2022. "The Fascinating World of Fungi." *BBC*, December 12. Accessed November 01, 2023. https://www.youtube.com/watch?v=LV7pPAhyiUQ&ab_channel=BBCIdeas.

Blesin, Julia-Maria, and Wiebke Möhring. 2016. Wissenschaftliche Innovation als narrativer Gegenstand. Kommunikative Herausforderungen von biobasiertem Kunststoff an die Wissenschaftskommunikation. In *Die Sprachen des Materials. Narrative – Theorien – Strategien*, edited by Friedrich Weltzien and Martin Scholz, 183–202. Berlin: Reimer.

Braun, Veit. 2021. Die Neuerfindung des Rades? Zur Rolle der Innovation in der Bioökonomie. In *Bioökonomie(n). Ethnografische Forschungszugänge und Felder*, edited by Lukas Fehr and Reinhard Johler, 53–76. Tübingen: Tübinger Vereinigung für Volkskunde e. V.

Chan, Emily, and Bella Webb. 2023. Stella McCartney-Backed Leather Alternative Mylo Halts Production. *Vogue*, June 30. Accessed November 05, 2023. https://www.voguebusiness.com/sustainability/stella-mccartney-backed-leather-alternative-mylo-halts-production-bolt-threads-kering-ganni-adidas-lululemon.

Commission of the European Communities. 2000. Green Paper Environmental Issues of PVC. Brussels.

Deadwood. 2023. Mycelium Collection. Accessed November 01, 2023. https://www.deadwoodstudios.com/pages/mycelium-collection.

Deadwood Studios. 2023. DEADWOOD SS24 Runway Show. *Copenhagen Fashion Week 2023*. Accessed November 15, 2023. https://www.youtube.com/watch?v=usLvW-2MgImA&ab_channel=DeadwoodStudios.

Dworsky, David, and Victor Köhler. 2014. Directors. The Next Black – A Film about the Future of Clothing. *AEG*. Accessed September 15, 2022. https://www.youtube.com/watch?v=XCsGLWrfE4Y&ab_channel=AEG.

DW News. 2020. Vegan Mushroom Leather Fashion from Indonesia. *Global Ideas*. Accessed November 15, 2023. https://www.youtube.com/watch?v=oe3Vwnnp-VA&ab_channel=DWNews.

Elbein, Asher. 2020. That Mushroom Motorcycle Jacket Will Never Go out of Style. *The New York Times*, September. Accessed August 03, 2023. https://www.nytimes.com/2020/09/16/science/fungus-leather.html.

Excellence Magazine. Nd. Hermès and the first leather bag… derived from mushrooms. Accessed June 06, 2024. https://www.excellencemagazine.luxury/hermes-and-the-first-leather-bag-derived-from-mushrooms/

Fehr, Lukas. 2021. Zwischen Ressourcen, Politiken und Vorstellungen der Zukunft. Kulturwissenschaftliche Perspektiven auf Bioökonomie. In *Bioökonomie(n). Ethnografische Forschungszugänge und Felder*, edited by Lukas Fehr and Reinhard Johler, 9–22. Tübingen: Tübinger Vereinigung für Volkskunde e. V.

Fries, Ben. 2013. Director. The Future of Fashion. *I-D*. Accessed September 15, 2023. https://www.youtube.com/watch?v=yzKM_DXfOBA&ab_channel=i-D.

Garcia-Pardo, Gabrielle. 2016. You Didn't Know Mushrooms Could Do All This. *National Geographic*, July 13. Accessed August 17, 2023. https://www.youtube.com/watch?v=-BIcKBKJ8uro&ab_channel=NationalGeographic.

Gazzola, Patrizia, Enrica Pavione, Roberta Pezzetti, and Daniele Grechi. 2020. Trends in the Fashion Industry. The Perception of Sustainability and Circular Economy: A Gender/Generation Quantitative Approach. *Sustainability* 12(7): 2809. https://doi.org/10.3390/su12072809.

Goormaghtigh, Maryam. 2017. Director. Fashion Geeks. *ARTE Documentary Series*. a_BAHN (FR), Tarantula (LU), ARTE (FR).

Grushkin, Daniel. 2015. Meet the Woman Who Wants to Grow Clothing in a Lab. *Popular Science*, May 17. https://www.popsci.com/meet-woman-who-wants-growing-clothing-lab/.

Hahn, Jennifer. 2021. Hermès Creates Mycelium Version of Its Classic Leather Victoria Bag. *Dezeen*, March 18. Accessed October 19, 2023. https://www.dezeen.com/2021/03/18/hermes-mycelium-leather-victoria-bag-mycoworks/.

Hall, Jacob. 2021. This Hermès Bag Is Partly Made from Mushrooms. *The Outlet*, March 17. Accessed May 22, 2024. https://www.the-outlet.com/posts/hermes-mushroom-leather-bag.

Haneef, Muhammad, Luca Ceseracciu, Claudio Canale, Ilker S. Bayer, José A. Heredia-Guerrero, and Athanassia Athanassiou. 2017. Advanced Materials from Fungal Mycelium: Fabrication and Tuning of Physical Properties. *Scientific Reports* 7: 41292. https://doi.org/10.1038/srep41292.

International Advisory Council on Bioeconomy. 2020. Global Bioeconomy Policy Report (IV): A Decade of Bioeconomy Policy Development around the World. Secretariat of the Global Bioeconomy Summit 2020. Berlin.

Jones, Mitchell, Antoni Gandia, Sabu John, and Alexander Bismarck. 2021. Leather-Like Material Biofabrication Using Fungi. *Nature Sustainability* 4(14), January: 9–16. Accessed August 20, 2023. www.nature.com/natsustain.

Kaplan-Bie, Jessie Hannah. 2018. Solution based post-processing methods for mycological biopolymer material and mycological product made thereby. US patent 20,180,282,529.

Küchler, Susanne. 2015. Materials: The Story of Use. In *The Social Life of Materials. Studies in Materials and Society*, edited by Adam Drazin and Susanne Küchler, 267–282. London/New York: Bloomsbury Academic.

Lange-Berndt, Petra. 2002. Gummi. In *Lexikon des Materials. Werkstoffe der modernen Kunst von Abfall bis Zinn*, edited by Monika Wagner, Dietmar Rübel, and Sebastian Hackenschmidt, 131–136. München.

Layrolle, Pierre. 2011. Calcium Phosphate Coatings. In *Comprehensive Biomaterials. Metallic, Ceramic and Polymeric Biomaterials 1*, edited by Paul Ducheyne et al., 223–230. Amsterdam, Netherlands: Elsevier. https://doi.org/10.1016/B978-0-08-055294-1.00024-6.

Live Kindly. Nd. Hermès Mushroom Leather Luxury Bag to Launch by End of Year. Accessed June 06, 2024. https://www.livekindly.com/hermes-mushroom-leather/

Lofrano, G., Meric, S., Balci, G., and Orhon, D. 2013. Chemical and Biological Treatment Technologies for Leather Tannery Chemicals and Wastewaters: A Review. *Science of Total Environment* 461–462: 265–281.

Luxiders. Nd. Hermès launches a mushroom-based leather bag. Accessed June 06, 2024. https://luxiders.com/hermes-mushroom-bag/

Materials Innovation Initiative. 2023. 2022 State of the Industry Report. Next-Gen Materials. Accessed January 30, 2024. https://materialinnovation.org/reports/2022-state-of-the-industry-report-next-gen-materials/.

Menkes, Suzy. 2022. Mycoworks – Dr. Matthew Scullin. *Creative Conversations Podcast*, July 19.

Morby, Alice. 2016. Aniela Hointink Creates Dress from Mushroom Mycelium. *Dezeen*, April 1. Accessed July 01, 2023. https://www.dezeen.com/2016/04/01/aniela-hoitink-neffa-dress-mushroom-mycelium-textile-materials-fashion/.

Müller, Jörg, Heinz Engel, and Markus Blaschke. 2007. Assemblages of Wood-Inhabiting Fungi Related to Silvicultural Management Intensity in Beech Forests in Southern Germany. *European Journal of Forest Research* 126(4): 513–527. https://doi.org/10.1007/s10342-006-0157-5.

MycoTech[A]. Biofabricating sustainable Material. Accessed June 06, 2024. https://mycl.bio/

MycoTech[B]. This Fashion presents Harmony by combining Art, Nature, and Technology. Accessed June 06, 2024. https://mycl.bio/collaboration/apa-kabar/

MycoWorks[A]. Nd. Grow the Future of Materials. Accessed June 06, 2024. https://www.mycoworks.com/

MycoWorks[B]. The Making of Fine Mycelium. Accessed November 01, 2023. https://www.mycoworks.com/the-making-of-fine-mycelium.

MycoWorks[C]. Nd. Sylvana. Accessed November 01, 2023. https://www.mycoworks.com/materials#sylvania.

MycoWorks [D]. Nd. See Inside the Lab Growing Mushroom Leather. *Freethink*, July 7. Accessed November 01, 2023. https://www.youtube.com/watch?v=FR24sXyO6ow&ab_channel=MycoWorks.

MycoWorks[E]. Nd. Grow the Future of Materials. The Key to Low Environmental Footprint. Overview of the Fine Mycelium™ process. https://www.mycoworks.com/life-cycle-assessment#environmental-impact.

MycoWorks[F]. 2024. Imagine one day being able to grow material. *LinkedIn*, Accessed August 22, 2024. https://www.linkedin.com/posts/mycoworks_imagine-one-day-being-able-to-grow-material-activity-7224528700350849024-oxmV?

Mylo[A]. Nd. Meet Mylo. Accessed June 06, 2024. https://mylo-unleather.com

Mylo[B]. How Mylo Is Made. Accessed June 02, 2024. https://mylo-unleather.com/material/.

Mylo[C]. Nd. Life Cycle Assessment. Accessed November 01, 2023. https://mylo-unleather.com/stories/what-is-a-life-cycle-assessment-lca.

Mylo[D]. Nd. Products. Accessed November 05, 2023. https://mylo-unleather.com/products/.
Nayak, Rajkishore, Long Nguyen, Asis Patnaik, and Asimananda Khandual. 2021. Fashion Waste Management Problem and Sustainability: A Developing Country Perspective. In *Waste Management in the Fashion and Textile Industries*, edited by Rajkishore Nayak and Asis Patnaik, 3–30. The Textile Institute Book Series. Elsevier.
O'Connor, Kaori. 2005. The Other Half: The Material Culture of New Fibres. In *Clothing as Material Culture*, edited by Susanne Küchler and Daniel Miller, 41–60. Oxford & New York: Berg.
Objcts.io. n.d. What's Mylo? The Mushroom Leather. Accessed June 02, 2024. https://objcts.io/en-de/pages/whatsmylo.
Oiljala, Leena. 2014. BIOCOUTURE Creates Kombucha Mushroom Fabric for Fashion & Architecture. *Pratt. Make the Future Here*, September 9. https://web.archive.org/web/20150619063637/http://bkaccelerator.com/biocouture-creates-kombucha-mushroom-fabric-fashion-architecture/.
Okie, Suz. 2021. These Materials Are Replacing Animal-Based Products in the Fashion Industry. *World Economic Forum*, October 6. Accessed November 09, 2023. https://www.weforum.org/agenda/2021/10/these-materials-are-replacing-animal-based-products-in-the-fashion-industry/.
Oluwaseun Adetunji, Charles, Olugbemi Olaniyan, Osikemekha Anthony Anani, Abel Inobeme, and John Tsado Mathew. 2021. Environmental Impact of Polyurethane Chemistry. In *Polyurethane Chemistry: Renewable Polyols and Isocyanates*, ACS Symposium Series, edited by American Chemical Society, 393–411. Washington, DC: ACS. https://doi.org/10.1021/bk-2021-1380.ch014.
Piñatex. Nd. FAQs. Ananas Anam. Accessed June 03, 2024. https://www.ananas-anam.com/faqs/.
Postrel, Virginia. 2020. *The Fabric of Civilization: How Textiles Made the World*. New York: Basic Books.
Preuss, Simone. 2017. Nachhaltige Textilinnovationen: Kaffeefasern. *Fashionunited*, June 3. Accessed November 01, 2023. https://fashionunited.ch/nachrichten/business/nachhaltige-textilinnovationen-kaffeefasern/2017070311716.
Pucker, Ken. 2023. Why Mushroom Leather (and Other New Materials) Are Struggling to Scale. Business of Fashion. July 13. Accessed August 14, 2024. https://www.businessoffashion.com/opinions/sustainability/next-generation-materials-innovation-mylo-bolt-threads-mushroom-leather/
Raman, Jegadeesh, Da-Song Kim, Hyun-Seok Kim, Deuk-Sil Oh, and Hyun-Jae Shin. 2022. Mycofabrication of Mycelium-Based Leather from Brown-Rot Fungi. *J. Fungi* 8(3): 317. https://doi.org/10.3390/jof8030317.
Rath, P., and Bay. 2015. *The Why of the Buy: Consumer Behavior and Fashion Marketing*. New York: Bloomsbury Publishing Inc.
Remy, Nathalie, Eveline Speelman, and Steven Swartz. 2016. Style That's Sustainable: A New Fast-Fashion Formula. *McKinsey Report*, October 20. Accessed August 14, 2024. https://www.mckinsey.com/business-functions/sustainability/our-insights/style-thats-sustainable-a-new-fast-fashion-formula.
Sangosanya, Annah-Ololade. 2022. Leather growth on liquid medium.
Textile Academy. Accessed August 14, 2024. https://class.textile-academy.org/2022/annah-sangosanya/FinalProject/05_LiquidCulture/
Schaub, Hans. 2009. Der Zunderschwamm. Rohstoff für ein altes Kunsthandwerk in Rumänien. *Tintling*, Ausgabe 59/2: 21–31.
Schwartzberg, Louie, dir. 2019. *Fantastic Fungi*. United States.
Spellmeyer, Gunnar. 2016. Materialimpulse. Wie sich das entwerferische Denken mit dem Material formt. In *Die Sprachen des Materials. Narrative – Theorien – Strategien*, edited by Friedrich Weltzien and Martin Scholz, 37–45. Berlin: Reimer.

Statista Research Department. 2023. Market Volume of Polyurethane Worldwide from 2015 to 2022, with a Forecast for 2023 to 2030. *Statista*. Accessed November 05, 2023. https://www.statista.com/statistics/720341/global-polyurethane-market-size-forecast/.

Stella McCartney[A]. The first MyloTM garments created from Vegan Mushroom Leather. Accessed June 06, 2024. https://www.stellamccartney.com/gb/en/stellas-world/the-worlds-first-mylo-garments-created-from-vegan-mushroom-leather.html

Stella McCartney[B]. The Frayme Mylo™, the world’s first luxury handbag made from mycelium. Accessed June 07, 2024. https://www.stellamccartney.com/us/en/stellas-world/frayme-mylo-mycelium-bag.html

Teisseire, Benjamin. 2024. “Mycoworks: Le Spore Chic à la Conquete du Luxe.” *Biomateriaux. Europa Star*, January. Accessed January 31, 2024. https://www.europastar.ch/le-dossier/horlogerie-et-environnement/1542-mycoworks-le-spore-chic-a-la-conquete-du-luxe.html.

The Economist. 2018. What Will People Wear in the Future? *Economist Films*. Accessed November 01, 2023. https://www.youtube.com/watch?v=uMOAbNfmEuo.

Tonti, Lucianne. 2023. “Plant or Plastic? How to Decode Vegan Leather Alternatives. *The Guardian*, February 28. Accessed January 31, 2024. https://www.theguardian.com/lifeandstyle/2023/mar/01/plant-or-plastic-how-to-decode-vegan-leather-alternatives.

Tsing, Anna Lowenhaupt. 2015. *The Mushroom at the End of the World: On the Possibility of Life in Capitalist Ruins*. Princeton: Princeton University Press.

Varkki, Albert. 2024. Mushroom Leather. *Von Baer*, April 13. Accessed June 03, 2024. https://vonbaer.com/blogs/blog/mushroom-leather.

Vacano, Bernhard, Hannah Mangold, and Christian Seitz. 2021. Kunststoffe im Kreislauf. *Chemie in unserer Zeit* 55 (6): 374–385. Weinheim: Wiley- VCH GmbH.

van der Haak, Bregtje. 2018. Director. Where the Future of Fashion Is Headed. *VPRO Documentary*. Accessed November 05, 2023. https://www.youtube.com/watch?v=DUFjz4GoIEw&ab_channel=vprodocumentary.

VenturePreneurs. 2020. Mushrooms Are Now the New Leather! *CNA Insider*, March 18. Accessed November 01, 2023. https://www.youtube.com/watch?v=ykWIACD6u8E&ab_channel=CNAInsider.

Waltz, Emily, and Nature Biotechnology. 2022. This Mushroom Leather Is Being Made into a Hermès Handbag. *The Scientific American*, March 28. Accessed November 02, 2023. https://www.scientificamerican.com/article/this-mushroom-leather-is-being-made-into-hermes-handbags/.

Weltzien, Friedrich and Scholz, Martin. 2016. Was das Material über das Design erzählt. Vorwort. In *Die Sprachen des Materials. Narrative – Theorien – Strategien*, edited by Friedrich Weltzien & Martin Scholz, 9–13. Reimer: Berlin.

Williams, Ellie, Cenian, Katarzyna, Golsteijn, Laura, Morris, Bill and Scullin, Matthew L. 2022. Life cycle assessment of MycoWorks’ Reishi™: the first low-carbon and biodegradable alternative leather. *Environmental Sciences Europe*, volume 34, Article number: 120.

Wood, Jane. 2019. Bioinspiration in Fashion—A Review. *Biomimetics* 4(16). doi:10.3390/biomimetics4010016

Woodward, Sophie. 2005. Looking Good: Feeling Right – Aesthetics of the Self. In *Clothing as Material Culture* edited by Küchler, Susanne and Miller, Daniel, 21–40. Berg: Oxford & New York.

ZVNDER: Quilt. Accessed November 01, 2023. https://shop.zvnder.com/quilt-verschiedene-groessen