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Designing Customizable Malleability and Padding in Fungal Textiles

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Abstract. This paper presents our investigation into methods to create fungal textiles with variable cushioning and flexibility properties, for differing technical and experiential characteristics. Fungal materials have generated rising interest in design communities over the past several years, resulting in applications in packaging, building, insulation, fashion and more due to their circular lifecycle and tunable customization on a myriad of properties and scales. In the fashion industry, these novel materials have been used as leather alternatives with a broad range of applications to the human form. Imitating conventional textile behavior, these applications, however, usually retain the same characteristics throughout the breadth of the material, a departure from the dynamic living organism it was created from. We aim to bridge this gap by endowing a singular fungal textile with multiple properties, serving the dual function of highlighting its organic origins and reducing the material complexity often required to achieve such versatility in a single material. Specifically, we present our design exploration to create localized support and flexibility in fungal textiles. We explored two techniques of creating fungal textiles, investigating diverse fungal species, growth and manufacturing methods, and post-processing techniques. The new techniques and unique properties of these materials suggest promising applications in areas such as assistive wearables, enhancing both user and planetary wellbeing.

Keywords: Fungal Textiles · Sustainability · Biodesign · Material Driven Design · Customization

1 Introduction

Materials grown from living sources like fungi offer sustainable solutions as well as unique benefits for product applications in their customization, permeability, and sensory experiences (see, for an overview, Camere & Karana 2018; Karana et al. 2018, Manan et al. 2021). Mycelium, the assimilative body of fungi that grows below ground in large networks, provides nutrients, communication and support to the fruiting bodies above ground. It can be grown into a flexible material (see, for example, Raman et al. 2022; Danninger et al. 2022) or solid structures (see Elsacker et al. 2020; Jones et al. 2020 for examples) depending on the structure of pure mycelium or its colonization of different substrates such as agricultural waste, sawdust, and cloth. Its unique heat resistant and

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hydrophobic properties have led to stiffer foam and composite applications in packaging (e.g., Ecovative), interiors (e.g., GROWN bio), sound insulation (e.g., MOGU), fitness accessories (Fraxinea), and more pliable ones in fashion (e.g., Mylium, Mylo, SQIM).

1.1 Fungal Textiles

Designers such as Aniela Hoitink have used fungi to grow mycelial discs and mold into custom clothing forms, leading to the development of MycoTex (NEFFA; Hoitink 2022). Helena Elston has combined mycelium with discarded textiles to create clothing that is compostable. Eden Power Corp, Hermes, Gucci and Stella McCartney have all used fungi based materials for their fashion collections. Many current consumer facing applications of fungal materials today are focused on fashion textiles at the luxury level, using industrial scale processes to produce leather alternatives (see Amobonye et al. 2023 for a table of companies). These fungal textiles hold the potential to be formed into custom shapes with differential patterning and properties for specific areas of flexibility or cushioning, facilitating novel material experiences and sustainable solutions to people's everyday products. However, current fungal textiles that have been created as leather alternatives maintain similar properties throughout without enabling more dynamic variation (Fig. 1). To achieve varying three-dimensional patterns within the same mono-material fungal textile, layering techniques can be used after material making, as demonstrated in a conceptual, never-commercialized woven yoga mat with three-dimensional patterns for user alignment and support (Lululemon Athletica 2021). However, this approach requires additional processing, rather than conformally fabricating the material in its final form and properties.

Fig. 1. Left: MycoTEX jacket by NEFFA, Middle: Amadou hat from Eden Power Corp, Right: Ephea® Radicle (©SQIM)

To bridge this gap, we present our explorations with various forms of fungi, both the hidden mycelia and the visible fruiting body towards the goal of differential patterning for varied stiffness, flexibility, and cushioning within the same material.

2 Literature Review

2.1 The Making of Fungal Materials: A Brief Overview

The body of research on fungal material making spans three categories (Gandia et al. 2021): (1) fungal material harvesting from the trama (an inner layer of the stiff fruiting body) of wild basidiocarps, (2) liquid state fermentation of pure mycelium, and (3) solid state fermentation through the use of substrates that could generate composite or mostly pure forms of mycelium depending on harvested area. The former two can lead to the production of more flexible, textile-like material, and the latter which would suit stiffer applications (Vandelook et al. 2021).

Within category 1, select fungal fruiting bodies, for example that of hoof fungi, have been explored as material, more commonly in traditional craft practices (Gandia et al. 2021). Craftspeople harvest this hoof fungi from beech forests yearly and carve off the top layer to expose the trama underneath which is then pounded and stretched. The resulting suede-like material, known as *amadou*, has shown promising absorptive and anti-inflammatory properties and has been fashioned into hats, wound patches, fly-fishing bait, and tinder by craftspeople (Peger 2001). Recently for category 2, submerged fermentation or liquid state fermentation using pure liquid cultures of mycelia, sometimes in bioreactors, has been emerging as a way to produce large quantities of flexible mycelial hides (Elsacker, Vandelook, & Peeters 2023) by first inoculation in static liquid culture and then growth in shaking incubators to allow for continued nutritional uptake (Adamatzky, et al. 2021). These require very controlled laboratory conditions but present a lot of potential in terms of scale and form. In category 3, mycelium material companies (like Ecovative) have used a form of solid-state fermentation to create aerial mycelium for leather alternatives. Aerial mycelium is where the mycelium is encouraged to grow further out of the substrate material into large foams that are then rolled and flattened alternately to create thicker biomaterial through the use of CO2 gradients, airflow, and other factors (Appels & Camere et al. 2019; Elsacker, Vandelook, & Peeters 2023).

2.2 Effect of Fungals Species and Substrates

Common species explored through these three processes are wood decaying white rot fungi including *Ganoderma lucidum*, *Schizophyllum commune*, *Trametes versicolor*, and *Pleurotus ostreatus*. These species are used in growing mycelium largely because of their ability to decay lignin found in woody materials to get to the cellulose and hemicellulose (Elsacker et al. 2020). Some species, like *Ganoderma lucidum* and *Fomes fomentarius* (used in the production of amadou as mentioned earlier), have health related properties for anti-inflammatory or anti-microbial effects used in Eastern medicine or in traditional Translyvanian craft practices (Ekiz et al. 2023; Pegler 2001). Common ways to create composite materials with mycelium include using bran, beechwood sawdust, rapeseed straw, hemp hurd, and even organic waste materials as substrates. Increasing sugar levels in the growth environment promotes faster growth, but the tradeoff in increased sugar concentration is the likelihood of faster growing contaminants also propagating, necessitating a rigorous sterile environment. In growing fungi with substrate material, more difficulty for the mycelium to break down the substrate could lead to stiffer material

with increased chitin concentration (Haneef et al. 2017). In general, the presence, size and orientation of natural fibers influence the stiffness of the resulting fungal material (Manan et al. 2021; Elsacker et al. 2019).

2.3 Post-processing of Fungal Materials

Fungal materials exhibit different properties depending on its state, plasticization (using glycerol) (Appels & Wösten 2021), deacetylation, cross linking and tanning (Jones et al. 2021), and heat treatment (Appels & Camere et al. 2019) methods applied. These properties can be fluidly changed to confer various stiffness/resistance or flexibility qualities depending on the required material outcomes. Varying the percentage of glycerol, for example, can change the material from brittle, to natural, to elastomeric (Appels et al. 2020). Different coatings with oils and films can also be added afterwards to preserve and confer hydrophobic and antimicrobial properties (see Elsacker et al. 2020 for examples). Materials able to be kept alive (sans the baking or heat pressing treatments) (Chang et al. 2019) show responsiveness to mechanical and optical stimuli (Adamatzky et al. 2021) and self-healing capabilities when rehydrated or put in nutrient media (Elsacker, Zhang, & Dade-Robertson 2023) presenting a promising avenue for *living regenerative artifacts* (Karana et al. 2023; Giaccardi and Karana 2015).

3 Methodology

The Material Driven Design (MDD) method (Karana et al. 2015) helped guide our material explorations. MDD suggests material tinkering (Parisi et al. 2017) as an essential activity throughout the design process. Explorative material tinkering gave way to more systematic tinkering that then fed into how the resulting properties would best meet human needs through later formgiving and concept explorations. Over the course of 9 months, the first author undertook an extensive exploration of two most promising fungal textile processes using different fungal sources: fungi from slant cultures (Exploration 1) and fungi from fruiting bodies (Exploration 2). Work requiring inoculation (Exploration 1) was performed in a biosafety level 1 biolab, while work with fruiting bodies (Exploration 2) was mostly performed in a materials lab, with only the end processes for both being done in a biolab. Even though the two processes were conducted separately, they occurred in parallel and cross-informed each other's development pathways and our understanding of textile material possibilities from fungi. Below we share our protocols and tacit knowledge obtained through these processes.

3.1 Exploration 1: Material Experimentation with Grown Mycelia from Cultures

Petri dishes were inoculated with samples taken from slant cultures that had been kept in a fridge. After at least 5 days, incisions were taken from the petri dishes and inoculated into large Erlenmeyer flasks containing 200 mL of liquid media according to the protocol in (Elsacker, Zhang, & Dade-Robertson 2023). Based on previous literature two species were used initially, *G. lucidum* (Bae et al. 2021) and *S. commune* (Appels et al. 2020). However, the *G. lucidum* strain, while growing quite well on the petri dish, did not

translate over to liquid cultures and was discontinued. Subsequent growth rounds were done with *S. commune*, testing out various liquid media compositions. The highest sugar content with 10% malt extract broth (MEB) yielded the fastest and most robust formation of the mycelial skin layer (with similar optimal growth on hydrogels seen in Gantenbein et al. 2023), but 8% MEB was chosen as a more moderate compromise because of concerns around contamination, as motivated in Table 1. See Fig. 2 for the overall process diagram.

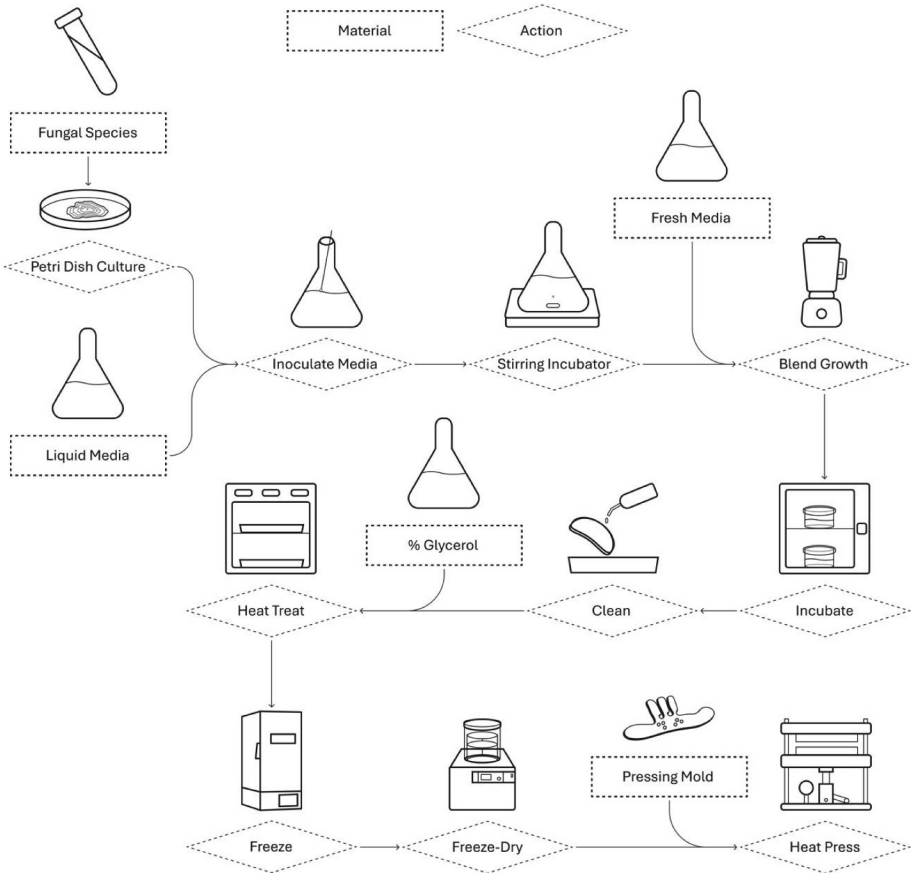

Fig. 2. Making process diagram of fungal textiles with liquid cultures

The flasks of liquid culture were incubated in static, stirred, and shaken conditions due to workarounds with equipment availability in the lab. It was found that stirring in the flask with a magnetic stirrer at 350 rpm produced the most consistent and even growth. After incubation in the flasks for at least 9 days, the cultures were blended with 100–400 mL of fresh liquid media in a Waring blender. It was found that 10 0mL of fresh media was sufficient while 400 mL led to slightly more growth, but had more danger of contamination and spillage in the blending process.

We observed that cultures containing the foam produced after blending yielded thicker and more cushion-like end mycelium material. Subsequent rounds also tried adding anti-foam which produced spottier and less consistent growth, confirming the helpful presence of foam. The new blended media was divided evenly over several new containers which included flat glass petri dishes, the same Erlenmeyer flasks, and tall crystallization glasses. The crystallization glasses were found to yield the best surface area to volume ratio for growth and provide sufficient height for the aerial mycelium to be contained in. Containers were incubated in both light and dark environments, with the dark environment yielding slightly less fruit body formation, although still some if the cultures were left too long.

After at least 5 days of incubation in the new containers, the resulting mycelium skins were removed from the culture, washed with water and cleaned with a cell scraper to remove the bottom gelatin-like layer that had formed. The mycelium was then deactivated at 60 degrees Celsius, either pressed and dried between parchment paper and a DIY press with plasticization afterwards, or directly in a percentage glycerol solution for 48 h. Mycelium in the varying percentages of glycerol followed material behavior similar to the ones obtained by Appels et al. (2020). 9% glycerol was chosen to be most applicable for a wearable context, in line with the conclusions in Table 1. Moisture trapped in the press made it more prone to contamination. Directly adding glycerol kept the material from sticking to surfaces and at approximately similar thicknesses, so conducting deactivation and plasticization at the same time without pressing was chosen as ideal. Samples prepared from that method were then freeze-dried and heat-pressed in a similar manner to those which will be outlined in Exploration 2. The resulting material can be seen in Fig. 3. The below table (Table 1) indicates various conclusions drawn from the variables iterated upon during this process.

3.2 Exploration 2: Material Experimentation with Blended Fruiting Bodies

In this exploration, we followed a similar method to the one presented by Nakauchi et al. (2023) of preparing mycelium pulp with a variety of different fruiting bodies. A Waring blender was used in place of an ultrasonicator due to lack of equipment availability. 200g of white button mushrooms were initially blended with varying glycerol percentages in 100mL of water and subsequently oven dried at 40 degrees Celsius. The resulting material was leather-like with significant shrinkage and curling done in molds. Bleaching was tried with store bought 3% hydrogen peroxide and UV light and also with 2% NaOH. 2% NaOH yielded faster results and a tan-yellow color, but the bleaching route was not pursued as the initial dark material color was deemed satisfactory and due to concerns about leftover chemical traces in the potential material applications. Because of the lack of predictability with oven drying, it was also discontinued and other methods for creating different textures and concept forms were pursued. See Fig. 4 for the overall process diagram.

Subsequent trials to replicate the foam variable shown in the grown process were made using freeze-drying with the blended pulp (Nakauchi et al. 2023). Mixtures were frozen after blending for at least 24 h and then freeze-dried at 0.303 mbar and −55 deg Celsius. Freezing at colder temperature -80 degrees Celsius versus 0 degrees Celsius in the 24 h before freeze-drying yielded a less moist material, most likely due to increased

Table 1. Takeaways from fungal textile explorations with grown mycelia from cultures.

Growth Media GPYM, 2% MEB, 8% MEB, 10% MEB	GPYM (Glucose Peptone Yeast Medium) shows slow and steady growth in separate chunks but starts to slow down at a smaller thickness. MEB shows faster growth from one central chunk but fruits earlier. Higher % MEB leads to thicker growth with less fruiting bodies, but no noticeable difference between 8% & 10%. 10% has more issues with contamination
Incubation Environment Static, Shaken, Stirred	Stirred incubation produced more consistent growth
Growth Container Erlenmeyer flasks, Glass petri dishes, Crystallization glasses	Tall petri dishes lead to more consistent and less deformed growth
Growth Composition Higher biomass, Coffee grounds, Activated charcoal	Higher biomass leads to faster and thicker initial growth. Substrate addition (coffee grounds) separates from material sections of pure mycelium. Activated charcoal promotes earlier fruiting and adds slight colored texture
Light No light, light	Presence or absence of light doesn't seem to make too much of a difference in 8% or 10% MEB in initial incubation. After blending, low light inhibits some fruiting
Foam No foam, Foam layer, Anti-foam	Layering the foam created after blending on top can lead to added thickness, more even, cushiony material. Material density still dependent on growth time. Need to have sufficient starting biomass for the foam to stay. Anti-foam causes uneven growth
Deactivation In paper press, In glycerol	Pressed drying helps prevent deformation but also leads to trapped moisture and potential contamination. All sugars should be washed off. Thin layers need a sheet between to prevent sticking to plate. Deactivation in glycerol maintains more thickness and prevents deformation
Glycerol Concentrations 3%, 6%, 9%, 16%	3% and 6% feels like the material is in danger of cracking, 16% feels too moist to the skin, 9% is ideal

sublimation of various oils present in the mixture. The resulting material had a memory foam-like quality which could be heat pressed to contain both cushion-like and leather-like qualities within the same piece (Fig. 5; Fig. 6). Varying the thicknesses, coatings, mold infills and patterns, temperatures, and durations for heat pressing was done to optimize for the two separate material qualities of padding and flexibility. In addition,

Fig. 3. Left: Flat sample of grown mycelia textile, Middle: Interaction with flat sample, Right: Pressed textures on grown samples

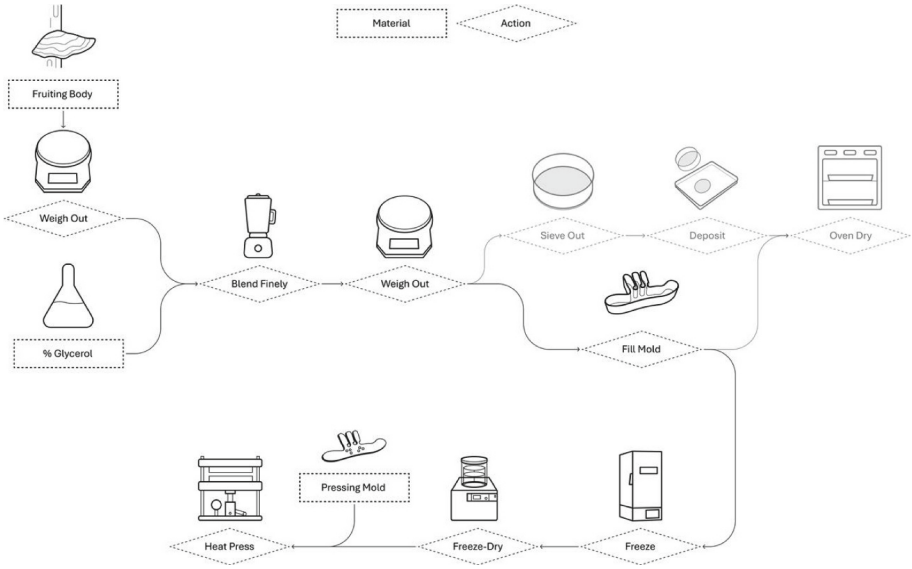

Fig. 4. Making process diagram of fungal textiles with blended fruiting bodies

all materials made using this fruitbody method displayed some property changes with surrounding environmental changes in humidity (e.g., if it was raining that day) with more "stickiness".

A variety of customizable patterns were tried out to test which ones separated from the pressing molds cleanly after heat pressing. We also evaluated how varying the thickness and weight of the pulp mixture in the freeze-drying molds, corresponding to benchmarking by either volume or density, might affect the durability and surface quality of the final pressed material. Varying the pressing molds and pressing factors (time, temp and coating) was looked into for the finer details of surface finish. Figure 5 above demonstrates the conclusions drawn during the freeze-drying and heat-pressing processes summarized at the end of Table 2.

The unpressed areas remained like a padded foam while the pressed areas were more leather-like for the white button mushrooms. Several bracket fungi were also blended

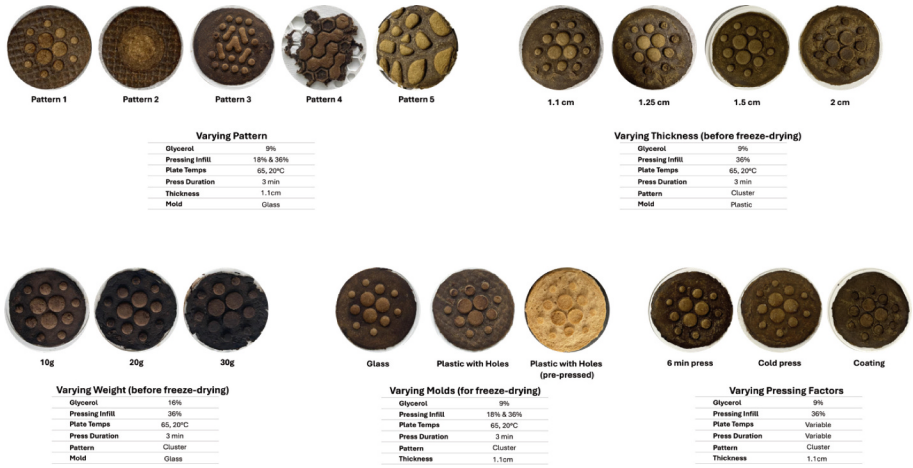

Fig. 5. Heat press experiment tracking for blended fruiting body (white button)

using this process which yielded much more padding and cotton-like properties both before and after heat pressing (Fig. 6).

4 Discussion

In this paper, we showed diverse techniques for differing qualities of padded support and flexibility within the same fungal material, with the parallel processes informing each other during development. During the material tinkering process, procedural knowledge and insights gained through the making of a foam-like quality in liquid culture led to similar aspirations in the fruiting body process which was achieved through freeze-drying. From there, different localized material properties could be obtained through heat pressing on both of the end results. Overall, the fruiting body process (Exploration 2) yielded a material that was easier to prototype with due to its quick turnaround time and simpler method to simulate a target thickness. Conversely, the inoculum-grown mycelium process (Exploration 1) produced more robust properties in elasticity and bending but was more difficult to simulate target thickness.

Reflecting first-hand on the experiential qualities of these fungal materials, several distinctive qualities stand out characterizing their materials experience (Karana et al. 2014). These materials possess a textile-like form, providing a soft and pliable surface. This quality makes these fungal materials particularly interesting for applications requiring direct contact with the body. Additionally, their adaptable texture allows them to conform to various shapes and surfaces, an attribute that can be exploited to create products with customized fits and enhanced comfort. A notable characteristic of these materials is their memory foam-like quality, which can be heat-pressed to achieve both cushion-like softness (padding quality) and selective firmness within the same piece. This versatility offers significant advantages, particularly in the creation of items that require both cushioning for comfort and a firm surface for support; one could also imagine a combination with even stiffer composite fungal materials. However, some

Table 2. Takeaways from fungal textile explorations with blended fruiting bodies

Types of Fungus White Button, Snow Fungus, Bracket Fungi	White button has better cohesion and a pleasant color. Snow fungus has a cushion like quality, but breaks apart. Bracket fungi has a cotton-pad like quality and cohesion
Processes Vacuum forming, Freeze-dry, Bleaching	Vacuum forming creates thin, even material, but difficult to remove from drying surface. Freeze-drying creates memory-foam like material with less bounce back. Freezing at colder temperatures beforehand yields less sticky material, probably because of more sublimated glycerol content. Bleaching with NaOH changes the deep brown color to more taupe-yellow
Oven Dry - Glycerol Concentrations 2%, 3%, 6%, 9%, 16%	2%, 3% and 6% lead to plastic-like material. 9% feels a bit more moist but does not feel like it'll crack when folded. 16% too moist
Oven Dry - Weight/Thickness 10 mL to 100 mL, 4 mm to 14 mm	Thicker layers more prone to cracking and noticeable stiffness difference with lower percentages of glycerol. More weight also leads to increased deformation in the oven drying process
Oven Dry - Molds Varying shape and texture	Grease needs to be applied to aid removal from the larger molds. Varying texture difficult with uneven shrinkage
Freeze Dry - Thickness 1.1 cm, 1.25 cm, 1.5 cm, 2 cm	Thicker can lead to material breakage during pressing. Similar results appeared for denser mixtures by weight
Freeze Dry - Molds Varying height, material	Need to be taller than material thickness to account for any bubbling over that occurs. No difference whether plastic or glass. Similar % glycerol conclusions as above
Heat Press Pattern, Infill, Temp, Duration, Coating	Too intricate of a pattern is difficult to remove. Lower infill leads to crosshatch pattern, 36% smoother. Need grease coating to aid material removal. Higher temp and longer duration leads to more color change. Beeswax coating helps with retaining surface finish

challenges also need to be addressed. The stickiness of the material from the fruiting body (white button) can complicate handling and finishing processes, potentially limiting its use in applications where a smooth, non-tacky finish is desirable. Moreover, the fragility of fungal materials raises concerns about their durability and suitability for long-term use, prompting a need for further development or integration with existing industry processes to enhance their strength and resilience. Despite these challenges,

Fig. 6. Left: Flat sample of white button fruiting body textile, Middle: Interaction with flat sample of shelf fungi fruiting body textile, Right: Pressed textures on samples from both white button and bracket fungi fruiting bodies

the unique combination of comfort, adaptability, and versatile surface properties makes these fungal materials promising candidates for applications in wellbeing, particularly in the development of assistive wearables and other products that enhance user comfort and support. By harnessing the unique properties of fungal textiles, we can develop sustainable solutions that benefit both human and planetary health, addressing an increasingly urgent concern within textile research and industries (see, for an overview, McQuillian & Karana 2023).

Potential categories of needs in patients suffering from dexterity affected diseases have been highlighted in previous research interviews and could include temporal needs (with swelling and pain following a circular loop from morning to night), differing localization of pain points per person and joint, and the changing nature of those throughout

Fig. 7. Prototypes of fungal textiles applied to assistive wearable forms

time (months or years) (Fang 2020). Research into various fungal species (like Ganoderma taugae and Phellinus linteus) for wound care and healing (Suarato et al. 2018; Su et al. 2005) as well as to atopic dermatitis (Hwang et al. 2012) show potential of skin-to-skin contact of certain compounds in fungal mycelia for anti-inflammation, antioxidant, and anti-tumor effects (see examples in Manan et al. 2021). For these reasons, our fungal textiles hold great potential for further exploration in assistive wearables, providing localized cushioning and support, along with additional potential therapeutic qualities. We propose this as an exciting direction for future study. Figure 7 showcases our initial prototypes in this promising area.

5 Conclusion

In conclusion, this paper has documented the exploration and development journey of a fungal textile material utilizing two distinctive methods: growing from culture and blending fruiting bodies. By critically comparing and reflecting on these approaches and their outcomes, we have identified and discussed the ability to vary padding and flexibility qualities within the material. Drawing inspiration from these qualities, we speculated on and prototyped potential applications for this material in the field of human wellbeing, particularly within assistive wearables. By leveraging the unique properties of fungal textiles, we can create sustainable solutions that promote both human and planetary health, aligning material life cycles with the needs of their users and the environment.

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