

Pure Mycelial Materials

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Contributor: Viraj Whabi, Bosco Yu, Jianping Xu

Modern efforts to influence materials science with principles of biology have allowed fungal mycelial materials to take a foothold and develop novel solutions for the circular bioeconomy of tomorrow. However, recent studies have shown that the value of tomorrow's green materials is not determined simply by their environmental viability, but rather by their ability to make the polluting materials of today obsolete. With an inherently strong structure of chitin and β -glucan, the ever-adaptable mycelia of fungi can compete at the highest levels with a litany of materials from leather to polyurethane foam to paper to wood. There are significant efforts to optimize pure mycelial materials (PMMs) through the entire process of species and strain selection, mycelial growth, and fabrication.

Keywords: biodegradable materials ; foams ; porous materials ; mycelium-based leathers ; mycelial films ; strain optimization ; hyphal structures ; liquid-state surface fermentation ; submerged fermentation ; solid-state fermentation

1. Towards Functional Fungi

The kingdom of fungi with its diverse portfolios of life cycles and adaptive morphology has been selectively cultivated since 600 AD ^[1]. Often characterized by unique cellular organizations, filamentous fungi consist of branching filaments called hyphae that form complex structures ^[2]. Composed of chitinous cell wall, the hyphae grow rapidly in networks, intaking nutrients to form a densely packed biomass known as mycelium ^{[2][3][4]}. Fungal mycelium has found recent attention from materials scientists due to its inherently robust structure which has been leveraged to create materials for construction, insulation, fashion, and other uses ^{[5][6][7]}. Combined with fungi's ability to upcycle wastes into constructive mycelia, the fabrication of these functional mycelial materials is cheap, non-energy intensive, and, most importantly, renewable ^[8]. As such, there is growing interest, both academic and industrial, in this field of 'fungineering' and developing better materials on-route to the transition toward a circular bioeconomy ^[9].

Preliminary research into this niche fungal biotechnology began with composites of mycelia and agricultural by-products. As the fungal biomass grows through the substrate, the natural secretions of the mycelia interlink them together into a reinforced material that is stronger than either of its parts ^[10]. These composite mycelial materials (CMMs) have already been deployed industrially and are widely regarded as feasible competitors to more established polystyrene packaging materials at lower embodied energy and carbon emission levels ^[8]. The current and future prospects of CMMs have been discussed in detail in notable review papers in recent years (See reviews ^{[11][12]}).

On the other hand, a newer family of materials made purely from mycelia has emerged and shown promising room for growth. Rather than combining with the substrate, these pure mycelial materials (PMMs) are separated from the substrate after cultivation or, in a few cases, exhaust the substrate entirely ^[13]. Start-ups such as Mycotech, Ecovative LLC, and Quorn have made strides using pure mycelia towards replacing leathers, high-performance foams, and meat ^{[14][15][16]}. However, for broad adoption, there are significant challenges in making PMMs the premier choice over conventional products with greater market history.

2. Techniques in the Cultivation of Mycelium

From industry to research, the growing interest in mycelial materials has necessitated evolution in fungiculture beyond targeting mushroom fruiting and toward maximizing hyphal production ^{[17][18][19][20]}. The various growing and processing methods offer specific advantages to create unique groups of materials with a wide scope of applications (as seen in **Figure 1**).

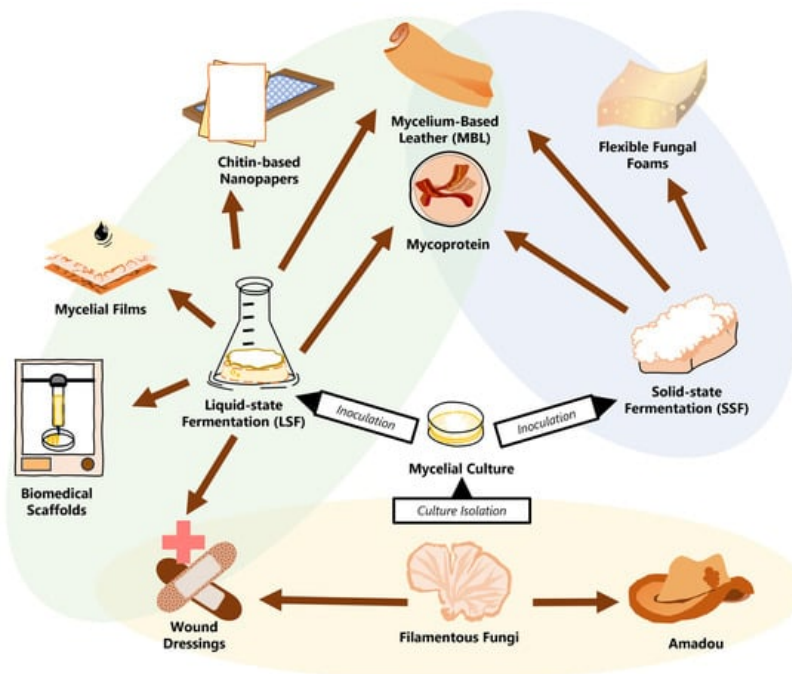


Figure 1. The current product portfolio of PMMs. From mushroom to mycelium, the cultures are isolated and then inoculated onto substrates. Functional materials (marked by brown arrows) are categorized by the type of fabrication, either directly from the fungal fruiting bodies (yellow) or with cultivated mycelial mats from LSF (green) or SSF (blue). Materials in overlapping sections can be made using multiple different techniques.

2.1. Solid-State Fermentation

Since ancient times, solid-state fermentation (SSF) has long been the ubiquitous method, as can be seen in the techniques making *kōji* from rice inoculated with *Aspergillus oryzae* or farming edible varieties of mushrooms [21][22][23][24][25]. The process involves inoculating grain or agricultural by-products with liquid fungal culture to create spawn that is left to fruit in fixed environmental conditions absent of free water [23][26]. Membrane filters made from cheesecloth or polycarbonate are sometimes used as a way to efficiently segregate the hyphal biomass from the substrate below; however, this can lead to reduced respiration rates [19][25]. Furthermore, careful consideration must be given to the diffusion of oxygen, as the formation of the intermediate wet hyphal layer can prevent oxygen from reaching the spawn and substrate below [25]. In mushroom farms, the solid substrate can live anew after harvest in the form of composites that use the combined strengths of the fungal hyphal network and the compacted substrate to create sustainable packaging and construction materials [5][12][22]. At PMMs, the spent substrate is not used, and it is instead separated from the mycelial mat that forms at the air/substrate interface [7][16][19]. Due to the high CO_2 in the growing environment, the mycelia forms a fluffy layer of aerial hyphae that branches upward out of the substrate for oxygen [16][23]. The resultant mat can thicken and strengthen due to the protein-rich environment provided by the complex and diverse agricultural substrate [7][16][19].

Static tray-based SSF has recently risen as the more popular cultivation method for large-scale production of mycelia, with the two largest manufacturers, MycoWorks and Ecovative LLC, filing patents involving solid substrates [16][27][28][29]. Looking to optimize their tray-based SSF processes, companies can take inspiration from the more established mushroom farming industry for decisions on substrate selection, environmental conditions, and mass production [21][30]. MycoWorks, in particular, has been able to scale up their mycelium-based leather (MBL) production using self-contained, shallow trays filled with inoculated sawdust that are vertically stacked in order to maximize space during growth [29]. Similarly, Ecovative's subsidiary My Foods has partnered with Canada-based Whitecrest Mushrooms Ltd. to develop "the world's largest vertical mycelium farm" and increase the yield of their MyBacon mycoprotein [31].

2.2. Liquid-State Fermentation

Liquid-state fermentation (LSF) offers alternative processes wherein concentrated nutritional liquid (or mostly liquid) media with guaranteed nutrient profiles are homogeneous and different from the heterogeneous solid substrates [17][18][19][20]. Common liquid media ingredients for wet lab applications such as potato dextrose broth, yeast malt dextrose broth, and blackstrap molasses are often used for the LSF of a variety of fungi [19][32][33][34]. Additionally, more complex solid substrate ingredients such as grains, straw, and sawdust can be homogenized with medium broth to create semi-solid

slurries [7][18]. However, LSF processes are not monolithic, as the choice of fermentation conditions can lead to drastically different end-products.

One distinct process is called submerged fermentation (SmF) and involves bioreactors with vast volumes of axenic culture under constant agitation to create large quantities of mycelia [34][35]. For fungi, SmF is preferred as a more efficient way to derive bioactive metabolites from species such as *Cordyceps militaris*, *Inonotus obliquus*, and *Schizophyllum commune* as compared to the conventional SSF [34][36]. While the amount of mycelia produced in such a short time is remarkable, the biomass is often prone to microbial contamination [24]. Additionally, the constant agitation limits the morphology of mycelia to small pellets suitable for mycoproteins but nothing larger [15][35][37]. Yet, Finland's VTT Technical Research Centre has shown in a pilot study that these disadvantages can be overcome with their novel MBL production. Their patent-pending SmF method utilizes a bioreactor to cultivate large quantities of mycelial slurry which is then dispensed at a rate of 1 m per minute before being dried, embossed, and processed [38].

A similar liquid-based method called liquid-state surface fermentation (LSSF) uses inoculated broth under static conditions to form mycelium at the interface between liquid and air. LSSF requires less overall energy than SmF and has the additional advantage of creating thick and tunable mycelial mats [13][20]. Fungal biomass derived from LSSF can be utilized in the creation of higher-order products such as MBLs as well as mycelial films, a new promising subgroup of PMMs that can be easily tuned to fit a wide range of functions such as binding agents, coatings, and membranes (See Section 3) [19][32][39]. Of note, LSSF has not yet been used for mass-scale production, but perhaps it could follow the vertical approach used by MycoWorks with assumedly cheaper costs attributed to lower material cost and less preparation. All current literature studies offer a limited perspective on LSSF, and it remains to be seen whether it can truly compare with either SmF or SSF at a wider scale. With their many differences, all of the methods are highly dependent on environmental conditions that need to be optimized for high yield and low variability. Optimizing these biotechnologies would offer the opportunity to tailor the performance of existing mycelial materials and pave the way towards many new ones [13][20]. These and potential future insights on cultivation substrates and conditions will result in PMMs with broad physical and chemical properties for increasingly broad applications.

3. The Growing Profile of Pure Mycelial Materials

3.1. Laying out the Design Space for PMMs

The recent interest in PMMs has steadily evolved into a large yet thoroughly uncharted collection of diverse materials the true potential of which is difficult to realize without an assay of the current prospects of these materials in their applications as leathers, foams, films, and more. One such method is through the process of materials selection, as introduced by Ashby and Cebon [40][41][42]. This process leverages materials data to systematically identify key qualities of comparable engineering materials in order to determine a desired materials profile that meets the necessary design function, objectives, and constraints [40][41][42]. The method of materials selection employs a measured approach in evaluating materials as they pertain to function, form, and design. To prioritize each one of these factors, the performance of materials is evaluated through relevant properties such as density or strength, as seen in **Table 1**, or a combination of many relevant properties in the form of a Material Property Index (MPI) [40][41][42]. The material to best fit the target application is the one which maximizes the optimization criteria of the MPI, while all others are ranked below in decreasing order [40][42].

Table 1. Common properties of materials, their definitions, and their units.

Materials Property	Definition	Unit
Density (ρ)	A material's mass per unit of volume.	kg/m ³
Percent elongation (%EL)	A material's deformation when it fractures due to a tensile load.	%
Ultimate tensile strength (σ_{UTS})	The maximum amount of strength a material can withstand under tension.	Megapascals (MPa)
Young's modulus (E)	The modulus of elasticity or the material's ability to stretch and deform.	Gigapascals (GPa)

The first step in crafting an MPI is to define an objective, typically minimum mass or density (ρ), which decides the direction of a design process. The next step comes with specific materials constraints as defined by the different components within the engineering design. For instance, materials like leathers need to be able to endure tensile conditions without reaching tensile rupture with a high enough ultimate tensile strength (σ_{UTS}). MPI₁ combines the

minimum mass objective as well as the constraints on tensile performance to create an index to rank how MBLs perform in comparison to other leathers [42][43].

$$\text{MPI}_1 = \sigma_{\text{UTS}} / \rho \quad \begin{array}{l} \text{Objective : minimize mass } (\rho) \\ \text{Constraint : strong enough to resist tensile rupture } (\sigma_{\text{UTS}}) \end{array} \quad (1)$$

There are limits to this index, as leathers, along with rubbers, wools, and silks, do not only endure uniaxial tensile loads, but need to have an intrinsic springiness controlled by their stiffness or Young's modulus (E) [43]. In line with the minimum mass design objective, MPI_2 assesses the ability to store high amounts of energy before springing back without failure [40] [43].

$$\text{MPI}_2 = \sigma_{\text{UTS}}^2 / E\rho \quad \begin{array}{l} \text{Objective : minimize mass } (\rho) \\ \text{Constraint : high enough elastic energy storage } (\sigma_{\text{UTS}}^2 / E) \end{array} \quad (2)$$

In order to visually grade the performance of different materials, various combination of properties (e.g., σ_{UTS} , E, ρ) for different materials are plotted using a material property chart (commonly known as an Ashby chart) in a log-log scale [40]. In **Figure 2** and **Figure 3**, the wide gamut of PMMs can be visually compared to the typical material families [7][19][20][32][33] [40][42][43][44][45][46][47][48][49][50][51]. Both MPI_1 and MPI_2 can be visualized as straight guidelines with defined slopes of 1 and $\frac{1}{2}$, respectively. In the case for MPI_2 , for instance, materials higher on the line maximize the energy storage, while those that lie on it are on equal footing [40]. It is evident from the laid out purple space that PMMs fit comfortably within a wide range of material families, including foams, elastomers, and polymers, depending on their species of origin, treatment process, and intended functions. Leveraging the principles of materials selection by way of materials property charts and MPis offers detailed performance metrics of novel materials like PMMs and outline the necessary trajectory for large-scale viability.

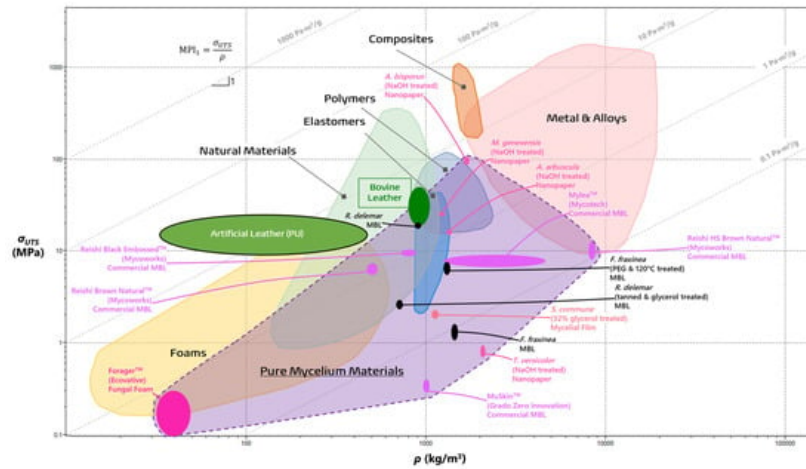


Figure 2. Material property chart comparing pure mycelial materials to typical materials families in terms of tensile strength (in MPa) against density (in kg/m³). The guideline signifies which materials optimize specific tensile strength with minimum mass designs. The image was generated using ANSYS, Inc. (<https://www.ansys.com/>, accessed on 20 January 2024).

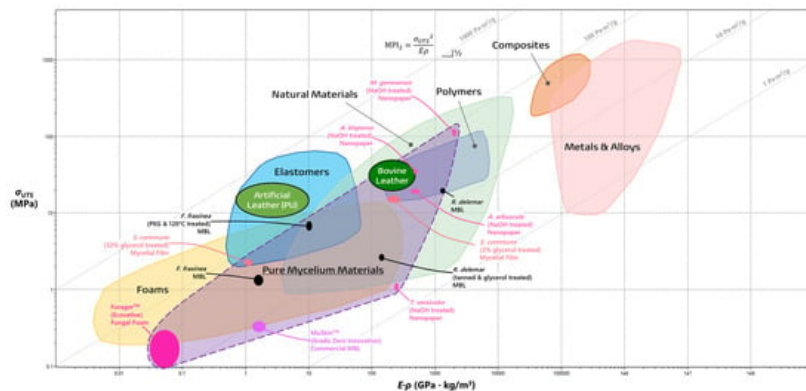


Figure 3. Material property chart comparing pure mycelial materials to typical materials families in terms of tensile strength (in MPa) against the product of density and Young's modulus (in GPa·kg/m³). The guideline signifies which materials optimize energy absorption per unit mass. The image was generated using ANSYS, Inc. (<https://www.ansys.com/>, accessed on 20 January 2024).

3.2. The Past, Present, and Future of Mycelial Textiles

In contrast with the textile's historical ubiquity, the current methods for modern leather production are becoming increasingly incompatible with society's vision of a better future [19][44][52]. There is a coming paradigm shift towards vegan leather, with the industry projected to overtake the market for traditional leathers by 2027 [44][53]. The emergence of the more affordable MBLs is spearheading this paradigm shift towards sustainable alternatives, challenging the dominance of their bovine and synthetic counterparts [44][53]. A comprehensive life cycle assessment conducted on MycoWorks' Reishi™ MBL revealed promising environmental credentials [29]. In their 2022 pilot-scale production, mycelium-based leather boasted a remarkably low carbon footprint of 6.2 kg of CO₂ equivalents per m², a stark contrast to the 32.97 kg of CO₂ equivalents per m² associated with bovine leather [29]. As production scales up, projections suggest an increase to 13.88 kg of CO₂ equivalents per m²; however, with optimized practices, this figure could plummet to as low as 2.76 kg of CO₂ equivalents per m² resulting from the transition to bio-gas free workflows [29]. Furthermore, research by Jones et al. highlights the superior cost-effectiveness of MBLs, with production costs estimated at a mere \$0.18–0.28 per m² compared to the substantially higher \$5.38–6.24 per m² for raw hides [44].

Fabricating fungal textiles has a storied history with Transylvanian craftspeople utilizing mushrooms of *Fomes fomentarius* and *Piptoporus betulinus* to create Amadou leathers as early as the 19th century [54][55]. In their fabrication, wild fruiting bodies are collected by hand, and then boiled in caustic lye solutions to makes the process of fabrication smoother. From there, the material is trimmed to shape by following the natural “grain” or growth direction, and then stretched to create products such as hats, belts, bags, etc. [54][56]. The resulting finish is a breathable material similar to felt and close to the color of bovine leather as a result of the high composition of melanin-like substances [57]. On the other side of the world, a Tlingit wall pocket from 1903 was discovered to have made from similar mycelial textiles by indigenous communities in British Columbia [58]. Upon examining the hyphal morphology of the wall pocket with a scanning electron microscope (SEM), the mycelia were determined to be characteristic of *Fomitopsis officinalis*, another bracket fungi not too dissimilar to those employed in Transylvania. While the methods of the Tlingit community are unclear, the process of evaluating the global ethnomycological usage of fungi elucidates how best to recontextualize these textiles for today [54][58]. Amadou has not been left in history, however, with fashion houses (as seen in **Figure 4a**) and bush crafters alike finding ways to recontextualize the material to modern needs [59][60].

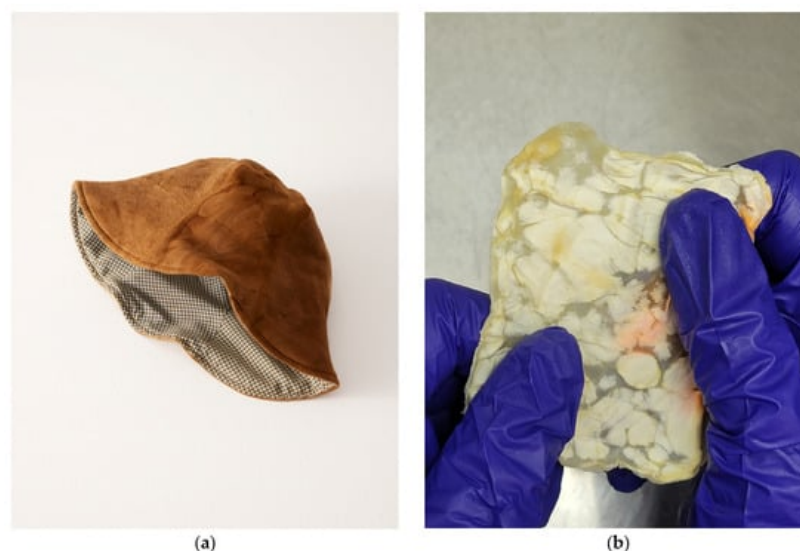


Figure 4. The product diversity of fungal textiles today. (a) The modern “Amadou tulip hat” made from the trama of *Fomes fomentarius* mushrooms sold by Eden Power Corp in 2022. (b) Lab-grown mycelium-based leather made from *Schizophyllum commune* mycelia grown through liquid-state fermentation and treated with polyethylene glycol.

To meet modern levels of demand, the process of producing MBLs has become more efficient than the mushroom-based artisanal handcrafting of Amadou through a more industrial, fermentation-based cultivation of mycelia. SSF and LSSF offer better control on the quality of the mycelial mats compared to historical manufacturing that depended on the seasonality of foraged mushrooms [20][53][54]. After the cultivation period is over, the mycelial material is typically separated from the substrate and then subjected to a range of treatment procedures [44]. Before any cross-linking or physical

treatment, the mycelial mats are pre-treated with hydrating agents such as glycerol, ethylene glycol, or polyethylene glycol (PEG) which also plasticize the hyphal fibers (as seen in **Figure 4b**) [19]. Next, the plasticized mats are immersed in alcohols or acetic acids in order to denature proteins and create sites for cross-linking [27][44]. Cross-linking with vegetable tannic acid allows the mycelia to more closely imitate the aesthetic, form, and function of conventional leathers [7][19][45][61]. In all cases, after chemical treatment, mechanical pressing of the materials is undertaken in an effort to further densify the mycelia with different methods using either heating or cooling to rapidly dry the mycelial mat [19][27][28].

According to investigations of the morphological, mechanical, and physiochemical characteristics of these materials, MBLs are more variable in comparison to bovine and synthetic leathers, as seen in **Table 2** [18][19][62]. Comparing individual properties such as density, elongation rate, tensile strength, and Young's modulus shows the different advantages of each material. While the tensile strengths of many MBLs are comparable to conventional leathers, the lower stiffness show that there is still a need to develop better post-processing methods for long-term feasibility [19][62]. Even those with high stiffnesses such as the treated *Rhizopus delemar* leather present failings with their poor elastic elongation rate [7].

Table 2. Physical properties of mycelium-based leathers versus conventional leathers.

Textile	ρ (kg/m ³)	%EL	σ_{UTS} (MPa)	E (GPa)	MPI ₁ (Pa·m ³ /g)	MPI ₂ (Pa·m ³ /g)	References
<i>Fomitella fraxinea</i> MBL (oak & bran substrate)	1580	4.30– 4.98	1.18– 1.62	0.00117– 0.00157	0.0875	893	[19]
<i>Fomitella fraxinea</i> MBL polyethylene glycol treated with 120 °C heat press (oak & bran substrate)	1460	13.87– 17.91	6.28– 8.14	0.00669– 0.00736	4.9	4990	[19]
<i>Rhizopus delemar</i> MBL (bread substrate)	884–922	1.7–2.3	19.04– 20.74	1.38–1.50	2.2	304	[7]
<i>Rhizopus delemar</i> MBL, tannin/glycerol treated (bread substrate)	695–739	14.5– 18.6	2.51– 2.93	0.199–0.201	0.378	5.14	[7]
MuSkin™ MBL (Grado Zero Innovation, Firenze, Italy) *	1000	17.3– 38.6	0.3–0.4	0.0018– 0.0028	0.0346	53.5	[52][62]
Reishi™ Brown Natural MBL (Mycoworks, Emeryville, CA, USA) *	480–540	16–36	5.6–7.4	-	1.27	-	[46][63]
Reishi™ Brown Natural High Strength MBL (Mycoworks) *	8400	55–80	8.8–12.5	-	0.125	-	[47][63]
Reishi™ Black Emboss MBL (Mycoworks) *	740–880	51–52	9.2–10.2	-	1.2	-	[48][63]
Mylea™ MBL (Mycotech; Aurora, CO, USA) *	1330– 4440	22–35	8–11	-	0.386	-	[49][50]
Artificial leather (Polyurethane composites)	340–470	-	9.4–24.5	0.012–0.036	12	87,700	[52][64][65]
Bovine leather	810– 1050	18–75	20–50	0.10–0.50	3.43	4560	[51]

MPI₁ highlights materials strong enough to resist tensile rupture (σ_{UTS}) that also meet the objective of minimum mass (ρ), which is measured in (Pa·m³/g). MPI₂ highlights materials with sufficiently high elastic energy storage (σ_{UTS}^2/E) that also meet the objective of minimum mass (ρ), which is measured in (Pa·m³/g). * indicates that the MBL is a commercial product.

Figure 2 visualizes materials that maximize their specific strength as defined with MPI₁ as a guideline with a slope of 1. Bovine leather only boasts an MPI₁ of 3.43 Pa·m³/g, while the artificial leather outperforms it by a whole order of magnitude [51][52][64][65]. The *F. fraxinea* leather improved impressively once cross-linked with PEG and heat pressed at 120 °C and even surpassed the reference bovine leather with an MPI₁ of 4.9 Pa·m³/g [19]. On the other hand, the virgin *R. delemar*, the second best MBL, was more successful than its treated counterpart (2.2 Pa·m³/g vs. 0.378 Pa·m³/g

respectively), demonstrating that not all species reap the same benefits from chemical treatments [62]. It is also worth noting that only two commercial MBLs, the Reishi™ Brown Natural and Black Embossed, were in the same range as the bovine leathers, while all the rest lagged in this metric of specific strength.

Figure 3 visualizes materials with optimal energy storage per unit mass and optimal performances are defined in the region with MPI_2 as a guideline and with a slope of $\frac{1}{2}$. Successful leathers can store great amounts of energy and combine the properties of tensile strength and Young's modulus in a ratio of σ_{UTS}^2/E [43]. Unfortunately, some commercial MBLs such as Reishi™ and Mylea™ do not have Young's modulus data, excluding them from this analysis [46][47][48][49][50]. Artificial leathers derived from polyurethane are in their own league, as the majority of MBLs do not come close [19][64][65]. The lone outlier, Raman et al.'s treated *F. fraxinea* mycelia, builds on its excellent specific strength properties with an extraordinary elastic storage ability ($MBI_2 = 4990 \text{ Pa}\cdot\text{m}^3/\text{g}$) that even supersedes bovine leather [19][43]. The success of these treated MBLs highlights the importance of researching chemical cross-linking, heat treatment, and species-based optimization if these materials are to supplant the conventional leathers of today.

Other mechanical properties, such as large scratch recoveries and high dynamic stress resistance, demonstrate the capability of the textile to withstand continual, repetitive loads. Furthermore, the lack of external fungal and bacterial growth on fabricated MBLs demonstrates their natural antifungal and antibacterial properties [62]. Just recently, MBLs have evolved from a niche idea to a growing trend in sustainable fashion embodied by the products of brands such as Adidas, Balenciaga, and Hermès [13][66]. With significant knowledge gaps in optimizing mycelium mat cultivation and post-processing procedures, the success of MBLs is heavily reliant upon future research prospects and could further expand the applications of MBLs to fit the materials needs of tomorrow.

3.3. Flexible Fungal Foams

Flexible fungal foams are promising candidates to replace insulation, petroleum-based foams, and wood composite cores. Presently, Ecovative LLC's patented Forager™ is the sole pure mycelial biofoam on the market which is reported to be completely "tunable" in terms of tensile strength, density, and fiber orientation [67]. These materials are fabricated through SSF with the addition of a vented void chamber on top of a tray. Since the void chamber is only accessible through the vents, a CO_2 gradient (3–7% concentration by volume) is introduced which encourages the mycelia to propagate through the vents and create an isolated mat of mycelia. Additionally, the relative humidity and temperature (29–35 °C) of the chamber are carefully chosen in order to mitigate primordial initiation which would compromise the mechanical properties of the foam. Before the foam is extracted, the mycelial mat is compressed to a chosen size and is left for an additional 72 h to densify and strengthen its fibers. Finally, the foam is separated from the substrate, dried at 43 °C, and, optionally, heat pressed to further densify the structure [16][68].

Presently, these foams are deployed as specialized textiles for the fashion industry that are marketed to be "insulating, water-repellent, and fire-resistant" [6][67][69]. Interestingly, a densified, closed-cell variety of Ecovative's foams has been shown to work as an excellent acoustic shield at a wide frequency range from 350 Hz to 4 kHz [70]. With the widespread employment of mineral wools, synthetic fibers, and petrochemical-derived polyurethane foams, these flexible fungal foams shine as greener and more sustainable alternatives [6][71]. Since there is only one player on the market, plans to apply these uniquely adaptable foams are nascent. The purported tensile strength (0.1 to 0.3 MPa), Young's modulus (0.6 to 2.0 MPa), and density (0.03 to 0.05 g/cm³) of the Forager™ material shows that it has a place, albeit small, in the foam material family, as seen in **Figure 2** and **Figure 3** [20][68]. It performs worse than bovine and artificial leathers in terms of specific strength ($MPI_1 = 0.447 \text{ Pa}\cdot\text{m}^3/\text{g}$) and elastic energy storage ($MPI_2 = 707 \text{ Pa}\cdot\text{m}^3/\text{g}$). However, these numbers should be taken with caution as they do not come from any peer-reviewed measurements in original research papers and are instead reported in Gandia et al.'s trend review paper alone [20].

Unlike other materials, the performance of foams relies greatly upon their relative densities, which describe whether they are open-celled or close-celled. Consequently, future potential is difficult to gauge with one overarching materials property index. If it was assumed that it behaved as an open-cell foam exhibiting Euler buckling (with relative densities between 0.01 to 0.3), a more general criterion could be created based upon the goal of maximizing energy absorption at a minimum mass. In fact, Bird et al. modeled such a criterion (MPI_3) during a case study on selecting the correct lightweight foam to make impact-absorbing helmets [72]. Here, E_s and ρ_s are the Young's modulus and density of the solid material, respectively, which can be determined with knowledge of the foam's relative density. Materials that optimize this index have high impact absorption at a minimum mass.

$$\text{MPI}_3 = E_s^{0.729} / \rho_s \quad \begin{array}{l} \text{Objective : minimize foam mass } (\rho_s) \\ \text{Constraint : high enough impact energy dissipation } (E_s^{0.729}) \end{array} \quad (3)$$

If competitiveness is the plan, then future fungal foams must target an optimization of this index as compared to other cushioning foams (e.g., open-cell polyurethane, polyethylene, neoprene, etc.) [40][43][72]. Of course, this is only one of many factors for assessing viability, but it is a defined threshold of success. For now, however, the biggest obstacle in realizing the current potential of these foams is the unfortunate dearth of materials testing and literature studies.

References

1. Kendrick, B. *Fungi and the History of Mycology*. In eLS; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2011; ISBN 978-0-470-01590-2.
2. Naranjo-Ortiz, M.A.; Gabaldón, T. *Fungal Evolution: Diversity, Taxonomy and Phylogeny of the Fungi*. Biol. Rev. Camb. Philos. Soc. 2019, 94, 2101–2137.
3. Gow, N.A.R.; Latge, J.-P.; Munro, C.A. *The Fungal Cell Wall: Structure, Biosynthesis, and Function*. Microbiol. Spectr. 2017, 5, FUNK-0035-2016.
4. Ainsworth, G.C.; Bisby, G.R.; Kirk, P.M.; Cannon, P.F.; Minter, D.W.; Stalpers, J.A. *Ainsworth & Bisby's Dictionary of the Fungi*, 10th ed.; CABI: Wallingford, UK, 2008; ISBN 978-0-85199-826-8.
5. Jones, M.; Bhat, T.; Huynh, T.; Kandare, E.; Yuen, R.; Wang, C.H.; John, S. Waste-Derived Low-Cost Mycelium Composite Construction Materials with Improved Fire Safety. *Fire Mater.* 2018, 42, 816–825.
6. Pelletier, M.G.; Holt, G.A.; Wanjura, J.D.; Greetham, L.; McIntyre, G.; Bayer, E.; Kaplan-Bie, J. Acoustic Evaluation of Mycological Biopolymer, an All-Natural Closed Cell Foam Alternative. *Ind. Crops Prod.* 2019, 139, 111533.
7. Wijayarathna, E.R.K.B.; Mohammadkhani, G.; Soufiani, A.M.; Adolfsson, K.H.; Ferreira, J.A.; Hakkarainen, M.; Berglund, L.; Heinmaa, I.; Root, A.; Zamani, A. Fungal Textile Alternatives from Bread Waste with Leather-like Properties. *Resour. Conserv. Recycl.* 2022, 179, 106041.
8. Livne, A.; Wösten, H.A.B.; Pearlmutter, D.; Gal, E. Fungal Mycelium Bio-Composite Acts as a CO₂-Sink Building Material with Low Embodied Energy. *ACS Sustain. Chem. Eng.* 2022, 10, 12099–12106.
9. Meyer, V.; Basenko, E.Y.; Benz, J.P.; Braus, G.H.; Caddick, M.X.; Csukai, M.; de Vries, R.P.; Endy, D.; Frisvad, J.C.; Gunde-Cimerman, N.; et al. Growing a Circular Economy with Fungal Biotechnology: A White Paper. *Fungal Biol. Biotechnol.* 2020, 7, 5.
10. Cairns, T.C.; Zheng, X.; Zheng, P.; Sun, J.; Meyer, V. Turning Inside Out: Filamentous Fungal Secretion and Its Applications in Biotechnology, Agriculture, and the Clinic. *J. Fungi* 2021, 7, 535.
11. Butu, A.; Rodino, S.; Miu, B.; Butu, M. Mycelium-Based Materials for the Ecodesign of Bioeconomy. *Dig. J. Nanomater. Biostructures* 2020, 15, 1129–1140.
12. Jones, M.; Mautner, A.; Luenco, S.; Bismarck, A.; John, S. Engineered Mycelium Composite Construction Materials from Fungal Biorefineries: A Critical Review. *Mater. Des.* 2020, 187, 108397.
13. Vandeloos, S.; Elsacker, E.; Van Wylick, A.; De Laet, L.; Peeters, E. Current State and Future Prospects of Pure Mycelium Materials. *Fungal Biol. Biotechnol.* 2021, 8, 20.
14. Bentangan, M.A.; Nugroho, A.R.; Hartantyo, R.; Iman, R.Z.; Ajidarma, E.; Nurhadi, M.Y. Mycelium Material, Its Method to Produce and Usage as Leather Substitute. WO2020136448A1, 2 July 2020.
15. Derbyshire, E.J.; Delange, J. Fungal Protein—What Is It and What Is the Health Evidence? A Systematic Review Focusing on Mycoprotein. *Front. Sustain. Food Syst.* 2021, 5, 581682.
16. Kaplan-Bie, J.H.; Bonesteel, I.T.; Greetham, L.; McIntyre, G.R. Increased Homogeneity of Mycological Biopolymer Grown into Void Space. WO2019099474A1, 23 May 2019.
17. Barabash, A.; Deschenko, V.; Chuk, O. Leather-like Material Biofabrication Using *Pleurotus ostreatus*. Ph.D. Thesis, National Aviation University, Kyiv, Ukraine, 2021.
18. Cartabia, M.; Girometta, C.E.; Milanese, C.; Baiguera, R.M.; Buratti, S.; Branciforti, D.S.; Vadivel, D.; Girella, A.; Babbini, S.; Savino, E.; et al. Collection and Characterization of Wood Decay Fungal Strains for Developing Pure Mycelium Mats. *J. Fungi* 2021, 7, 1008.

19. Raman, J.; Kim, D.-S.; Kim, H.-S.; Oh, D.-S.; Shin, H.-J. Mycofabrication of Mycelium-Based Leather from Brown-Rot Fungi. *J. Fungi* 2022, 8, 317.
20. Gandia, A.; van den Brandhof, J.G.; Appels, F.V.W.; Jones, M.P. Flexible Fungal Materials: Shaping the Future. *Trends Biotechnol.* 2021, 39, 1321–1331.
21. Gowthaman, M.K.; Krishna, C.; Moo-Young, M. Fungal Solid State Fermentation—An Overview. *Appl. Mycol. Biotechnol.* 2001, 1, 305–352.
22. Grimm, D.; Wösten, H.A.B. Mushroom Cultivation in the Circular Economy. *Appl. Microbiol. Biotechnol.* 2018, 102, 7795–7803.
23. Hölker, U.; Lenz, J. Solid-State Fermentation—Are There Any Biotechnological Advantages? *Curr. Opin. Microbiol.* 2005, 8, 301–306.
24. Machida, M.; Yamada, O.; Gomi, K. Genomics of *Aspergillus Oryzae*: Learning from the History of Koji Mold and Exploration of Its Future. *DNA Res.* 2008, 15, 173–183.
25. Rahardjo, Y.S.P. Fungal Mats in Solid-State Fermentation; Wageningen University: Wageningen, The Netherlands, 2005.
26. Fazenda, M.L.; Seviour, R.; McNeil, B.; Harvey, L.M. Submerged Culture Fermentation of “Higher Fungi”: The Macrofungi. In *Advances in Applied Microbiology*; Academic Press: Cambridge, MA, USA, 2008; Volume 63, pp. 33–103.
27. Kaplan-Bie, J.H. Solution Based Post-Processing Methods for Mycological Biopolymer Material and Mycological Product Made Thereby. WO2018183735A1, 4 October 2018.
28. Ross, P.; Scullin, M.; Wenner, N.; Chase, J.; Miller, Q.; Saltidos, R.; McGaughy, P. Mycelium Growth Bed with Perforation Layer and Related Method for Creating a Uniform Sheet of Mycelium from a Solid-State Medium. US20200196541A1, 25 June 2020.
29. Williams, E.; Cenian, K.; Golsteijn, L.; Morris, B.; Scullin, M.L. Life Cycle Assessment of MycoWorks’ Reishi™: The First Low-Carbon and Biodegradable Alternative Leather. *Environ. Sci. Eur.* 2022, 34, 120.
30. Thakur, M.P. Advances in Mushroom Production: Key to Food, Nutritional and Employment Security: A Review. *Indian. Phytopathol.* 2020, 73, 377–395.
31. Atlast Food Co. Partners with Whitecrest Mushrooms Ltd. to Scale Production of MyBacon® Strips. Available online: <https://myforestfoods.com/myblog/blog-whitecrest> (accessed on 19 February 2024).
32. César, E.; Canche-Escamilla, G.; Montoya, L.; Ramos, A.; Duarte-Aranda, S.; Bandala, V.M. Characterization and Physical Properties of Mycelium Films Obtained from Wild Fungi: Natural Materials for Potential Biotechnological Applications. *J. Polym. Environ.* 2021, 29, 4098–4105.
33. Jones, M.; Weiland, K.; Kujundzic, M.; Theiner, J.; Kählig, H.; Kontturi, E.; John, S.; Bismarck, A.; Mautner, A. Waste-Derived Low-Cost Mycelium Nanopapers with Tunable Mechanical and Surface Properties. *Biomacromolecules* 2019, 20, 3513–3523.
34. Petre, A.; Ene, M.; Vamanu, E. Submerged Cultivation of *Inonotus Obliquus* Mycelium Using Statistical Design of Experiments and Mathematical Modeling to Increase Biomass Yield. *Appl. Sci.* 2021, 11, 4104.
35. Cui, Y.Q.; van der Lans, R.G.J.M.; Luyben, K.C.a.M. Effect of Agitation Intensities on Fungal Morphology of Submerged Fermentation. *Biotechnol. Bioeng.* 1997, 55, 715–726.
36. Tang, Y.-J.; Zhu, L.-W.; Li, H.-M.; Li, D.-S. Submerged Culture of Mushrooms in Bioreactors—Challenges, Current State-of-the-Art, and Future Prospects. *Food Technol. Biotechnol.* 2007, 45, 221–229.
37. Bakratsas, G.; Polydera, A.; Nilson, O.; Chatzikonstantinou, A.V.; Xiros, C.; Katapodis, P.; Stamatis, H. Mycoprotein Production by Submerged Fermentation of the Edible Mushroom *Pleurotus ostreatus* in a Batch Stirred Tank Bioreactor Using Agro-Industrial Hydrolysate. *Foods* 2023, 12, 2295.
38. Szilvay, G.; Barrantes, M.A. Mycelium Leather: Sustainable Alternative for Leather. Available online: <https://www.vttresearch.com/en/news-and-ideas/alternative-leather-and-synthetic-leather-vtt-succeeded-demonstrating-continuous> (accessed on 19 February 2024).
39. Bae, B.; Kim, M.; Kim, S.; Ro, H.-S. Growth Characteristics of Polyporales Mushrooms for the Mycelial Mat Formation. *Mycobiology* 2021, 49, 280–284.
40. Ashby, M.F. *Materials Selection in Mechanical Design*, 5th ed.; Butterworth-Heinemann: Amsterdam, The Netherlands; Cambridge, MA, USA, 2017; ISBN 978-0-08-100599-6.
41. Ashby, M.F. Overview No. 80: On the Engineering Properties of Materials. *Acta Metall.* 1989, 37, 1273–1293.

42. Ashby, M.F.; Cebon, D. Materials Selection in Mechanical Design. *J. Phys. Arch.* 1993, 3, C7-1–C7-9.
43. Ashby, M.F.; Gibson, L.J.; Wegst, U.; Olive, R. The Mechanical Properties of Natural Materials. I. Material Property Charts. *Proc. R. Soc. Lond. A* 1995, 450, 123–140.
44. Jones, M.; Gandia, A.; John, S.; Bismarck, A. Leather-like Material Biofabrication Using Fungi. *Nat. Sustain.* 2021, 4, 9–16.
45. Appels, F.V.W.; van den Brandhof, J.G.; Dijksterhuis, J.; de Kort, G.W.; Wösten, H.A.B. Fungal Mycelium Classified in Different Material Families Based on Glycerol Treatment. *Commun. Biol.* 2020, 3, 334.
46. Lin, J.; Sadowy, S. Vartest Report on Mycoworks REISHITM Brown Natural; Vartest Laboratories: New York, NY, USA, 2020.
47. Lin, J.; Sadowy, S. Vartest Report on Mycoworks REISHITM Brown Natural—High Strength; Vartest Laboratories: New York, NY, USA, 2020.
48. Lin, J.; Sadowy, S. Vartest Report on Mycoworks REISHITM Black Emboss; Vartest Laboratories: New York, NY, USA, 2020.
49. Mylea Technical Data Sheet. Available online: <https://mycl.bio/storage/app/media/mylea/Mylea%20Technical%20Data%20Sheet.pdf> (accessed on 10 May 2023).
50. Kuijk, A. Biofabricated Mycelium Mylea Leather Sheets—HauteMatter. Available online: <https://www.hautematter.com/product-deck/mylea> (accessed on 5 October 2023).
51. GRANTA EduPack; ANSYS, Inc.: Cambridge, UK; Available online: <https://www.ansys.com/materials> (accessed on 20 January 2024).
52. Meyer, M.; Dietrich, S.; Schulz, H.; Mondschein, A. Comparison of the Technical Performance of Leather, Artificial Leather, and Trendy Alternatives. *Coatings* 2021, 11, 226.
53. Quito, A. Mushroom Leather: How Fungi Became Fashionable. Available online: <https://qz.com/emails/quartz-obsession/1849446383/mushroom-leather-how-fungi-became-fashionable> (accessed on 7 December 2022).
54. Papp, N.; Rudolf, K.; Bencsik, T.; Czégényi, D. Ethnomycological Use of *Fomes fomentarius* (L.) Fr. and *Piptoporus betulinus* (Bull.) P. Karst. in Transylvania, Romania. *Genet. Resour. Crop Evol.* 2017, 64, 101–111.
55. Pegler, D.N. Useful Fungi of the World: Amadou and Chaga. *Mycologist* 2001, 15, 153–154.
56. Hahn, J. Traditional Transylvanian Mushroom Leather Wraps Seating Collection by Mari Koppanen. Available online: <https://www.dezeen.com/2022/02/02/mari-koppanen-fomes-amadou-seating-design/> (accessed on 7 December 2022).
57. Kalitukha, L.; Sari, M. Fascinating Vital Mushrooms. *Tinder Fungus (Fomes fomentarius (L.) Fr.) as a Dietary Supplement. Int. J. Res. Stud. Sci. Eng. Technol.* 2019, 6, 1–9.
58. Blanchette, R.A.; Haynes, D.T.; Held, B.W.; Niemann, J.; Wales, N. Fungal Mycelial Mats Used as Textile by Indigenous People of North America. *Mycologia* 2021, 113, 261–267.
59. Amadou Tulip Hat—EDEN Power Corp. Available online: <https://web.archive.org/web/20220829223510/https://edenpowercorp.com/collections/fungus-yeasts-molds-and-mushrooms/products/pre-order-amadou-tulip-hat> (accessed on 24 May 2023).
60. Hordon How to Make Amadou Tinder. Available online: https://www.beaverbushcraft.co.uk/page_4140610.html (accessed on 24 May 2023).
61. Deeg, K.; Gima, Z.T.; Smith, A.; Stoica, O.C.; Tran, K. Greener Solutions: Improving Performance of Mycelium-Based Leather. Final Report to MycoWorks. 2017. Available online: https://bcgctest.files.wordpress.com/2018/03/gs_2017_mycoworks_finalreport.pdf (accessed on 20 January 2024).
62. Bustillos, J.; Loganathan, A.; Agrawal, R.; Gonzalez, B.A.; Perez, M.G.; Ramaswamy, S.; Boesl, B.; Agarwal, A. Uncovering the Mechanical, Thermal, and Chemical Characteristics of Biodegradable Mushroom Leather with Intrinsic Antifungal and Antibacterial Properties. *ACS Appl. Bio Mater.* 2020, 3, 3145–3156.
63. Scullin, M.; Rigas, N. A Story of Superior Quality. ReishiTM. 2020. Available online: <https://www.madewithreishi.com/stories/> (accessed on 20 January 2024).
64. Roh, E.K. Mechanical Properties and Preferences of Natural and Artificial Leathers, and Their Classification with a Focus on Leather for Bags. *J. Eng. Fibers Fabr.* 2020, 15, 155892502096882.
65. Eun, J.H.; Lee, J.S. Study on the NCO Index and Base Knitted Fabric Substrates on the Thermal, Chemical, and Mechanical Properties of Solvent-Less Formulations Polyurethane Artificial Leather. *J. Eng. Fibers Fabr.* 2020, 15, 1558925020916458.

66. Ettinger, J. Balenciaga Goes “Livestock-Free” With a New €9,000 Coat Made From Mycelium. *Ethos*. 2022. Available online: <https://the-ethos.co/balenciaga-mycelium-leather-coat/> (accessed on 20 January 2024).
67. Davidson, L. Ecovative Announces Partners to Bring Mycelium Foam to the Fashion Industry. Available online: <https://www.businesswire.com/news/home/20220322005069/en/Ecovative-Announces-Partners-To-Bring-Mycelium-Foam-to-the-Fashion-Industry> (accessed on 8 December 2022).
68. Greetham, L.; McIntyre, G.R.; Bayer, E.; Winiski, J.; Araldi, S. Mycological Biopolymers Grown in Void Space Tooling. Patent US11277979B2, 22 March 2022. Available online: <https://patents.google.com/patent/US20150033620A1/en> (accessed on 20 January 2024).
69. Compostable Foam: Breathable, Insulating, Water-Repellant|Ecovative. Available online: <https://www.ecovative.com/pages/foams> (accessed on 23 November 2023).
70. Pelletier, M.G.; Holt, G.A.; Wanjura, J.D.; Bayer, E.; McIntyre, G. An Evaluation Study of Mycelium Based Acoustic Absorbers Grown on Agricultural By-Product Substrates. *Ind. Crops Prod.* 2013, 51, 480–485.
71. Asdrubali, F.; Schiavoni, S.; Horoshenkov, K.V. A Review of Sustainable Materials for Acoustic Applications. *Build. Acoust.* 2012, 19, 283–311.
72. Bird, E.T.; Bowden, A.E.; Seeley, M.K.; Fullwood, D.T. Materials Selection of Flexible Open-Cell Foams in Energy Absorption Applications. *Mater. Des.* 2018, 137, 414–421.

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