Biodesign Innovation in Sustainable Footwear: Evaluating 3D-Printed Molds for Mycelium-based Composites Sole Development

Lida Aflatoony, Colorado State University, United States
Alexander Wood, Colorado State University, United States
Yan Vivian Li, Colorado State University, United States

Keywords: Footwear, Biodesign, Mycelium-based composite, 3D Printing, Mold Design

Concept and Context: The fashion industry ranks among the most environmentally damaging sectors, with the footwear segment particularly reliant on toxic synthetic materials, driven by excessive consumption, and burdened by non-biodegradable materials (Staicu et al., 2023). For that reason, many shoe companies worldwide are embracing sustainability by integrating bio-based and recycled materials into their products, as exemplified by brands like Rothy's®, Saye©, and Reebok®. Rothy's® uses 35% renewable outsoles, 30% bio-based and recycled insoles, and ocean-bound plastics to promote circularity (Rothy's, n.d.). Saye© crafts sneakers with bio-based vegan napa, bamboo, recycled plastics, and polyurethane, packaged in biodegradable materials (Saye, n.d.), while Reebok's® "Cotton + Corn" initiative, highlighted by the U.S. Department of Agriculture. (n.d.), uses corn and cotton to develop compostable shoes, addressing the 300 million pairs discarded annually in U.S. landfills. These efforts reflect the footwear industry's shift toward eco-friendly practices, reducing waste and reliance on non-renewable resources through innovative material use and production processes.

As the footwear industry shifts toward sustainable production methods, exploring alternatives, such as biomaterials, to non-sustainable materials becomes essential. Recently, mycelium-grown materials primarily containing cellulose have demonstrated the potential to significantly contribute to sustainable development goals. Mycelium-based composites (MBCs) are formed via the cultivation of fungi, resulting in a network of interconnected mycelium that surrounds and connects the discrete material to form a self-supporting composite. MBCs are primarily formed using wood-derived cellulose, the most compatible substrate, although researchers have investigated other nutrient-rich alternatives to support mycelium growth due to its diverse nutritional needs (Elsacker et al., 2019; Vašatko, 2022; Silverman et al., 2020). Although MBCs are widely used in interior design, furniture, art, and sculpture (Bonenberg et al., 2023), their application in fashion and footwear design remains underexplored. Drawing on prior research, this study leverages cellulosic substrates to enhance MBC applications in footwear design. It also seeks to optimize MBC growth within 3D-printed molds crafted to mirror the detailed structure of footwear soles. While various studies have used MBCs to create basic footwear soles with 3D-printed molds (Silverman et al., 2020; Rapagnani et al., 2024), no research has yet explored the specifics of sole design, such as the sole's intricate traction patterns, using advanced 3D-printed mold techniques. Funded by the

© 2025 The author(s). Published under a Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Agricultural Experiment Station, this experimental research continues to evolve across multiple phases.

Methods: The process started with designing diverse molds to mimic footwear sole parts, allowing researchers to assess the compatibility of mycelium-based composites molding with 3D-printing materials (polymer filaments). At this phase, it was essential to create preliminary testing shapes that accurately represent key technical features of the shoe, including the sole's outer bottom texture and fine traction patterns. Through this process, using Autodesk Fusion 360® 3D modeling software, three molds were created: (1) Three-part undulated sole mold (figure 1); (2) Five-part grip-pattern mold (figure 2); and (3) Mold protective sleeve (figure 3). The *Tree-Part Undulated Sole Mold*, featuring a simpler traction pattern than the *Five-Part Grip-Pattern Mold*, was tested first for MBC moldability. The *Five-Part Grip-Pattern Mold*, designed with intricate grip patterns like those found on Timberland® or Vans® sneakers for enhanced traction, required greater complexity. Additionally, the *Mold Protective Sleeve* was developed in the final stage of the process, prompted by mycelium growth outcomes observed in the earlier tests of the two initial molds. This sleeve also minimizes environmental contamination risks to the composite. These molds were engineered to create an ideal mycelium growth environment, with components gradually added or removed based on observations from each testing phase. The molds were designed with multi-way openings to simplify the demolding process and facilitate the removal of MBCs. The molds feature: (a) a self-healing injection port to minimize contamination risks; (b) a top lid, crafted from 1/8-in. laser-cut plexiglass, fitted into a frame to monitor mycelium growth; (c) a lid frame to secure the plexiglass; (d) screws and bolts to securely fasten each side of the mold; and (e) an air filter system. This system includes a threaded closure to firmly hold both poly-fil and filter paper. In the initial phase, molds were 3D printed using the Bambu Lab X1E 3D Printer with PLA filament (figure 4). However, in the final stages, autoclave-safe polycarbonate filament was adopted to transition the 3D-printed molds to a material capable of withstanding higher temperatures required for sanitation, ensuring optimal MBC growth.

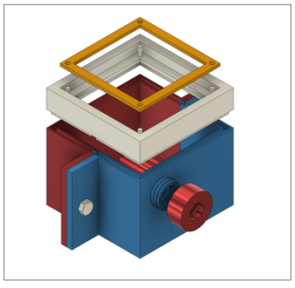

Figure 1.

Three-part mold.

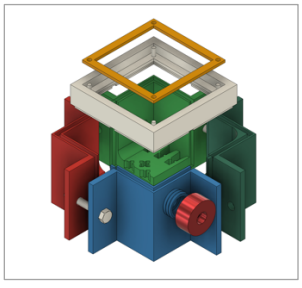

Figure 2.

Five-part mold.

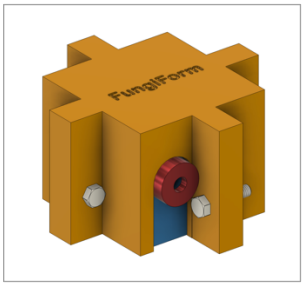

Figure 3.

Mold cover.

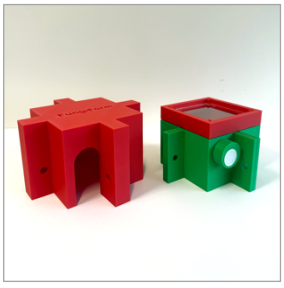

Figure 4.

3D printed molds.

© 2025 The author(s). Published under a Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

To initiate MBC growth, woodchips as cellulosic substrate was boiled in distilled water for 30 minutes, then air-dried until the surface was felt dry to the touch. Next, potato dextrose broth (PDB) was prepared and mixed with the substrate to enhance growth by supplying additional sugars to the MBC. Following this, the 3D-printed mold was sterilized with 70% isopropyl alcohol. The substrate was combined with PDB within the mold. Subsequently, the mold's sides and top lid were sealed by protective parafilm and secured with screws and bolts to prevent external contamination. The assembled mold and substrate were then autoclaved at 121°C for one hour. Afterward, the mold was cooled to room temperature before inoculating it with 4 ml of mycelium culture. MBCs developed within the mold in approximately three weeks.

Results and Future Objectives: Initially, untreated sawdust was employed as the substrate for the composite, without any nutrients such as potato dextrose broth (PDB). This lack of proper nourishment led to weak mycelium hyphae adhesion in the early composites. Enhanced composites incorporated potato dextrose broth (PDB) to supply additional sugars, fostering mycelium growth. This approach, supported by Jones et al. (2019), produced a denser mycelium network within the composite, resulting in improved bonding strength. Additionally, in the initial mold designs, the structure was vulnerable to external contamination from the surrounding environment. This vulnerability stemmed from openings on each side—despite being tightly secured with screw closures—as well as gaps around the lid and the lid's glass, which allowed airflow to introduce contaminants into the early composites. Adding a mold protective sleeve to fully seal the mold would significantly reduce exposure to external pollutants. Such a cover would also enable autoclaving, effectively eliminating any pathogens present in the substrate. Building on these findings, the study's future goal is to design a 3D-printed mold that shapes the entire footwear sole, integrates it with the shoe's upper part, and evaluates the result through usability testing.

© 2025 The author(s). Published under a Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

References

Bonenberg, A., Sydor, M., Cofta, G., Doczekalska, B., & Grygorowicz-Kosakowska, K. (2023). Mycelium-based composites: Study of acceptance. *Materials, 16*(6), 2164. https://doi.org/10.3390/ma16062164

Elsacker, E., Vandelook, S., Brancart, J., Peeters, E., & De Laet, L. (2019). Mechanical, physical and chemical characterisation of mycelium-based composites with different types of lignocellulosic substrates. *PLOS ONE, 14*(7), Article e0213954. https://doi.org/10.1371/journal.pone.0213954

Jones, M., Huynh, T., Dekiwadia, C., Daver, F., & John, S. (2019). Mycelium composites: A review of engineering characteristics and growth kinetics. *Journal of Bioresources and Bioproducts, 4*(4), 224–234. https://doi.org/10.12162/jbb.v4i4.014

Rapagnani, N., van Bezooijen, A., Borruso, L., Mimmo, T., & Bouaicha, O. (2024). Bio Design for Footwear Innovation: Growing Sneaker Components with Composite Mycelium-based Materials. Cambridge Open Engage. doi:10.33774/coe-2024-5cc7n This content is a preprint and has not been peer-reviewed.

Rothy's. (n.d.). *Sustainability*. Retrieved March 30, 2025, from https://rothys.com/pages/sustainability

Saye. (n.d.). *Our impact*. Retrieved March 30, 2025, from https://www.sayebrand.com/pages/our-impact

Silverman, J., Cao, H., & Cobb, K. (2020). Development of Mushroom Mycelium Composites for Footwear Products. Clothing and Textiles Research Journal, 38(2), 119-133. https://doi.org/10.1177/0887302X19890006 (Original work published 2020)

Staicu, S. L., & Pop, O. M. (2023). Stepping into sustainability: A study on the impact of the footwear industry and innovative solutions for a greener future. *Sustainability, 15*(20), 14954. https://doi.org/10.3390/su152014954

U.S. Department of Agriculture. (n.d.). *Shoes: BioPreferred program*. Retrieved March 30, 2025, from https://www.biopreferred.gov/BioPreferred/faces/pages/articles/Shoes.xhtml

Vašatko, H., Gosch, L., Jauk, J., & Stavric, M. (2022). Basic Research of Material Properties of Mycelium-Based Composites. *Biomimetics*, 7(2), 51. https://doi.org/10.3390/biomimetics7020051

© 2025 The author(s). Published under a Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.