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Materials Framing: A Case Study of Biodesign Companies' Web Communications

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Abstract
Advances in biodesign offer opportunities for developing materials for everyday products from living organisms, such as fungi, algae, and bacteria. Gaining widespread acceptance of new materials from the general public can be a lengthy process, making biodesign a high-risk pursuit with potentially significant economic, ecological, and social impacts. In this article, we conceptualize the notion of *materials framing* — combining knowledge from materials science, product design, and innovation management to create a communications strategy that accelerates popular adoption of novel materials. Which of its qualities will help orient users' understanding of the new material? What is the best way to present those qualities? An extensive analysis of nine biodesign companies' text and visual web communications revealed three core materials framing categories: material origins, fabrication processes, and material outcomes. We argue that these three categories expand the audiences' focus beyond mere outcomes to include an organism's design potential — a lens with which to gain a more comprehensive view of the possibilities the material from a living organism affords.

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Introduction[1]

Advances in biotechnology and the democratization[2] of biofabrication technologies[3] have inspired design communities the world over. Otherwise known as biodesign,[4] this new design practice intertwines biology and design, employing living organisms such as algae, bacteria, and fungi to synergistically develop materials and products. Over the last year, a sizeable corpus of biodesign research projects, exhibitions, and conferences[5] have addressed biodesign's technical[6] and methodological[7] challenges, as well as its potential[8] for creating biological and digital hybrid systems[9] and other biological futures.[10] In this vivid creative landscape, startups and SMEs[11] are demonstrating interest in this new industrial revolution,[12] seeking to expand opportunities to develop consumer products. Following the white, industrial biotechnology paradigm[13] used in biofuels,[14] food,[15] and biological tissues[16] production, these companies are advancing techniques to create novel materials from living organisms that are regenerative,[17] compostable, and able to displace commodity plastics.[18]

However, widespread global acceptance of new materials typically requires around twenty years,[19] and consumers' understanding and appreciation of them are critical to their market success.[20] Certain scholars in the field of materials and design[21] argue that when designing with a new material, understanding what that material can offer in terms of novel functions and experiences is of paramount importance.[22] Having that understanding of a material's potential can help organizations devise meaningful applications and ultimately support the introduction of the material to the public. There is, however, a gap in the literature regarding how to represent new materials to users to encourage their wider adoption.

In this article, we conceptualize the notion of *materials framing* by linking the fields of materials science, product design, and innovation management as a communication strategy to accelerate adoption of novel materials beneficial to society. We also illustrate how biodesign companies and manufacturers can operationalize materials framing. Through an extensive analysis of nine biodesign companies' text and visual website communications, we identified three categories to support the framing of novel materials: material origins, fabrication processes, and material outcomes. We conclude by discussing new research directions, such as the need for new microbial lexicon for biodesign and for digital support tools to explore and communicate an organism's design potential to the public.

Related Work

This section first presents the different branches of research in biodesign, product design, materials science, and innovation management that indicate the need for effective communications regarding new materials. It then introduces a number of tools and frameworks to support them.

Material Innovations in Biodesign

Biodesign, a new industrial paradigm for goods production in the 21st century,[23] entails harnessing biological organisms and applying biofabrication

1 Editorial notes: (1) *She Ji* uses American English. The narrative text of this article conforms to U.S. English. Many items in this article are proper nouns—the names and titles of projects and organizations. For these, we use the version of English in the name or title. (2) This article includes many trademarks for the names of companies, products, and services. In accordance with standard editorial practice, we have removed all trademark and copyright symbols from the narrative text. (3) The full original captions contain significant information on the source of images, as well as permissions, and image credits. We have edited the captions to clarify and simplify them for the reader. The full original captions appear at the end of this article as an appendix. Because the original captions include detailed and lengthy records of the research process, we left them as prepared by the authors, including trademark and copyright information required when rights holders granted permission to reproduce the images.

2 Theresa Jean Tanenbaum et al., "Democratizing Technology: Pleasure, Utility and Expressiveness in DIY and Maker Practice," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York: ACM, 2013), 2603–12, DOI: https://doi.org/10.1145/2470654.2481360.

3 Vladimir A. Mironov et al., "Biofabrication: A 21st Century Manufacturing Paradigm," *Biofabrication* 1, no. 2 (2009): 022001, DOI: https://doi.org/10.1088/1758-5082/1/2/022001.

4 Alexandra Daisy Ginsberg et al., *Synthetic Aesthetics: Investigating Synthetic Biology's Designs on Nature* (Cambridge, MA: MIT Press, 2014); William Myers, *Bio Design: Nature, Science, Creativity* (New York: Museum of Modern Art, 2012), 3–26.

5 Biofabricate, "Biofabricate Summit 2019," accessed April 23, 2021, https://www.biofabricate.events/summit; Carole Collet, curator, "Alive: New Design Frontiers" (Espace Fondation EDF, Paris, April 26–September 1, 2013), http://thisisalive.com/; Maurizio Montalti, curator, "Fungal Futures: Growing Domestic Bio-landscapes," (January 2014–December, 2015), http://www.fungal-futures.com/; Elvin Karana et al., eds., *International Conference of the Design Research Society Special Interest Group on Experiential Knowledge (EKSIG) 2017: Alive. Active. Adaptive* (Delft, Netherlands: Delft University of Technology, 2017), https://eksig.org/EKSIG2017.html.

6 Jürgen Groll et al., "Biofabrication: Reappraising the Definition of an Evolving Field," *Biofabrication* 8, no. 1 (2016): 013001, DOI: https://doi.org/10.1088/1758-5090/8/1/013001; Lorenzo Moroni et al., "Biofabrication: A Guide to Technology and

a b

Figure 1
(a) Mylo vegan leather from fungal mycelium; (b) limited release Mylo Driver Bag.

principles and techniques to develop materials and products for everyday use.[24] Serena Camere and Elvin Karana[25] provide a thorough overview of biodesign attempts over the last two decades, from speculative examples[26] to product applications.[27]

In the last decade, biodesign companies have accelerated the translation of biological materials into consumer products.[28] A new industrial model combining white biotechnology and bionics leads to rapid expansion in materials diversity[29] via a sustainable development production model.[30] The living organisms that play a role in these initiatives include fungi, bacteria, yeast, and algae.

Fungi is the largest living organism on earth.[31] It grows on diverse organic substrates, forming entangled networks of branching fibers called mycelium.[32] Mycelium,[33] which is the vegetative part of a fungus, is a composite, fibrous material mainly composed of natural polymers such as chitin, cellulose, and proteins.[34] There are numerous examples of the production of pure mycelium[35] and mycelium-based composites[36] in the works. For example, a recently announced partnership between Bolt Threads, Adidas, Lululemon, Stella McCartney, and Kering[37] aims to advance development of Mylo, a vegan "(un)leather" obtained from fungal mycelium, which will be available for purchase beginning in 2021 (Figure 1).

Bacteria are single-celled prokaryotic microorganisms widespread in nature, in soil and on plants.[38] They are easy to grow in a variety of environments, ranges of temperatures, and pH conditions, and rapidly replicate by absorbing nutrients from waste and renewable resources. It is easy to dismantle and genetically manipulate bacteria for strain improvement.[39] Bacteria are widely used in the fermentation industry.[40] Important bacteria biofabrication initiatives include the creation of pigments,[41] silk-like textile fibers,[42] flexible cellulose,[43] and bioleather.[44] For instance, in 2016 Laura Luchtman from Kukka Design Studio and Ilfa Siebenhaar of Studio Ilfa Siebenbaar started the Living Colour project[45] to explore the possibilities of natural textile dyeing using bacteria to produce pigments (Figure 2a). Recently, Living Colour teamed up with Puma Innovation for the soon-to-market Design to Fade line,[46] which entails coloring sportswear by

Terminology," *Trends in Biotechnology* 36, no. 4 (2018): 385–98, DOI: https://doi.org/10.1016/j.tibtech.2017.10.015; Matthew J. Pavlovich, Joshua Hunsberger, and Anthony Atala, "Biofabrication: A Secret Weapon to Advance Manufacturing, Economies and Healthcare," *Trends in Biotechnology* 34, no. 9 (2016): 679–80, DOI: https://doi.org/10.1016/j.tibtech.2016.07.002; Freek V.W. Appels et al., "Fabrication Factors Influencing Mechanical, Moisture- and Water-Related Properties of Mycelium-Based Composites," *Materials & Design* 161 (January 2019): 65–70, DOI: https://doi.org/10.1016/j.matdes.2018.11.027.

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8 Bahareh Barati and Elvin Karana, "Affordances as Materials Potential: What Design Can Do for Materials Development," *International Journal of Design* 13, no. 3 (2019): 105–23, http://www.ijdesign.org/index.php/IJDesign/article/view/3419; Elvin Karana, Valentina Rognoli, and Rubén Jacob-Dazarola, "The Role of Design in the Development of New Materials: Interview with Elvin Karana," *Diseña*, no.17 (August 2020): 46–55, DOI: https://doi.org/10.7764/disena.17.46-55.

9 Neri Oxman, *Material-Based Design Computation* (Cambridge, MA: Massachusetts Institute of Technology, 2010), 27–40; Jiwei Zhou et al., "Digital Biofabrication to Realize the Potentials of Plant Roots for Product Design," *Bio-Design and Manufacturing* 4 (September 2020): 113, DOI: https://doi.org/10.1007/s42242-020-00088-2.

a b

Figure 2
(a) Living Colour; (b) Puma in collaboration with Living Colour: Design to Fade.

a b

Figure 3
(a) Studio Blond & Bieber in collaboration with Ikea Virtual greenhouse, presented at Dutch Design Week, 2020; (b) Studio Blond & Bieber, Algaemy Bench No. 1.

cultivating bacteria directly on textiles. As the bacteria ferment the nutrients they feed on, they produce pigments that leave visible growth patterns (Figure 2b).

Algae are photosynthetic organisms that grow in a range of aquatic habitats, including lakes, ponds, rivers, oceans, and even wastewater. Algae can tolerate a wide range of temperatures, salinities, and pH values, various light intensities and other conditions in reservoirs or deserts. They can grow alone or in symbiosis with other organisms.[47] Algae are classified as macroalgae (seaweed) or microalgae.[48] Microalgae are microscopic single cells and may be prokaryotic, similar to cyanobacteria, or eukaryotic, like green algae.[49] Emerging initiatives use algae for design applications such as textiles pigments,[50] air purifier biofilms,[51] and foam fillers.[52] In 2014, Berlin-based design studio Blond & Bieber began to explore how microalgae could be used to create biodynamic color palettes for textile prints that change over time. Shoe prototypes by Germany's Trippen[53] and a biodegradable t-shirt currently sold by the English brand Vollebak[54] have used these pigments. Recently, Blond & Bieber collaborated with Ikea's Virtual Greenhouse project to create sustainable upholstery fabric for home interiors (Figure 3).[55]

As companies continue to develop sustainable materials generated from living organisms, they need better communication strategies to market them effectively, so that consumers adopt them into their everyday lives.

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19 Elicia Margaret Anne Maine, *Innovation and Adoption of New Materials* (PhD dissertation, Cambridge: University of Cambridge, 2000), 81; Elicia Maine, David Probert, and Mike Ashby, "Investing in New Materials: A Tool for Technology Managers," *Technovation* 25, no. 1 (2005): 16, DOI: https://doi.org/10.1016/S0166-4972(03)00070-1.

20 Ann Crabbé et al., "Transition towards Sustainable Material Innovation: Evidence and Evaluation of the Flemish Case," *Journal of Cleaner Production* 56 (October 2013): 68, DOI: https://doi.org/10.1016/j.jclepro.2012.01.023; Valentina Rognoli et al., "DIY Materials," *Materials & Design* 86 (December 2015): 693–95, DOI: https://doi.org/10.1016/j.matdes.2015.07.020; Carsten Herbes, Christoph Beuthner, and Iris Ramme, "Consumer Attitudes towards Biobased Packaging—A Cross-Cultural

Materials Acceptance: A Design-Driven Approach

Adoption of a new material generally requires a gestation period of twenty years or more from technical innovation, to first commercial application, and finally, widespread acceptance.[56] For example, market diffusion of early bioplastics or PLAs, discovered around 1890, did not take off in the packaging industry until the 1960s.[57] In their critique of bioplastics' widespread use and acceptance, Valentina Rognoli and her colleagues[58] refer to poor "material identity"—the public image of a material's unique aesthetics, technical and functional aspects, and potential applications. Material identity is considered an important contributor to the wider use of a new material and its overall acceptance.[59]

Recognizing this situation, material scientists and industries developing new materials have reached out to academics and professionals in art and design to guide the development of materials by both experiential and functional goals.[60] Design communities are continually evolving their ability to contribute scientifically to materials development through improved knowledge and skills in understanding, interpreting, envisioning, and designing for user experiences,[61] where design-driven innovation strategies[62] are a conceptual starting point.

In 2015, aware of the importance of bridging the technical and experiential aspects of materials in design, Elvin Karana and her colleagues[63] proposed the Material Driven Design (MDD) method as a strategy for creating meaningful material experiences and thus accelerating acceptance of new materials. The authors show the ways the four levels of material experiences—sensorial, interpretive, affective, and performative[64]— are integrated in the design of materials and products in synergy.[65] In a recent article, Bahareh Barati and Elvin Karana[66] describe some specific contributions that designers can make to collaborative materials development, such as revealing a material's potential for unique forms, functions, and experiences, as well as what can be done to it—its process-ability.

Do these aspects suffice as communicators of the unique qualities and benefits of a material generated from living organisms? What else could help to frame this new material, to provide it with some terrain of reference for new users? While framing has not been studied in the context of material innovations, a large body of research concerning new product development in the field of technology and innovation management exists, which helps ground the notion of *materials framing* in the context of biodesign.

Framing Innovation in Design

Framing is a communication approach that influences how individuals, groups, and societies organize, perceive, communicate, and reorient their thinking about particular issues or objects.[67] Several theories on innovation framing articulate how and why people adopt new ideas, practices, and tools. In Everett Rogers' notion of innovation theory,[68] an idea or product gains momentum over time and diffuses through a social system according to five perceived attributes—relative advantage, compatibility, complexity, trial-ability, and observability. Fred Davis[69] claims that ease in learning a new technology is not as relevant to the user as its perceived usefulness in increasing productivity.[70] And more recently, Diane Dormant's chocolate model for innovation, adoption, and change[71] introduces the concept of an innovation's perceived adaptability to the specific needs of the adopters.

Companies developing new products use Rogers's, Davis's, and Dormant's models extensively to frame their innovations. Such innovations are later communicated through mass media and interpersonal channels.[72] Use of such channels amplifies engagement by people who are not experiencing the product themselves.[73] However, successfully marketing a brand and its products to an audience that has no prior knowledge of it can be difficult.[74] Thus, companies that communicate their innovations predominantly through online channels must clearly articulate an innovation's advantages and the experiences it can afford.[75] Experiential product framing[76] is a strategy that uses sensorial stimuli to vividly persuade audiences of a new product's potential. This persuasion occurs via narratives rather than hard facts and analysis.[77]

Materials Framing

The term *materials framing* refers to a communication strategy that aids the creation of a common understanding of a novel material to promote its widespread appreciation. Jonathan Chapman emphasizes the role of material narratives when marketing a new material,[78] and Sylvia Machgeels[79] proposes a method for developing material narratives by focusing on a material's origins. When it comes to introducing materials from living organisms, there are barriers to overcome[80] in terms of, for example, established preconceptions of fungi and bacteria as filthy or unhealthy organisms.[81] Ceneic,[82] a London-based design agency promoting biodesign, recently introduced a new project called Biotours[83] in order to overcome such preconceptions. In the next section, we reveal opportunities for effectively framing materials from living organisms to promote their widespread acceptance in society.

A Study of Biodesign Companies' Web Communications

We present how biodesign companies currently frame new materials generated from living organisms and how these frames vary depending on the organism. In future studies, we aim to expand on our findings by exploring other communication mediums, such as social media and exhibitions.

Procedure

Case Selection

We searched multiple fields at the intersection of biology and design, including biodesign, bioart, DIYbio, biofabrication, and biotechnology. We screened these to collect examples of materials biofabricated for consumer products by using keywords[84] collected from recent scientific publications,[85] lectures,[86] and books.[87] We used the same terms to scrape the archives of online resources, including design blogs,[88] online magazines,[89] online curated exhibitions,[90] and events dedicated to biodesign.[91]

Comparative Study," *Journal of Cleaner Production* 194 (September 2018): 204, DOI: https://doi.org/10.1016/j.jclepro.2018.05.106; Sarah Wilkes et al., "Design Tools for Interdisciplinary Translation of Material Experiences," *Materials & Design* 90 (January 2016): 1228–30, DOI: https://doi.org/10.1016/j.matdes.2015.04.013; Mark A. Miodownik, "Toward Designing New Sensoaesthetic Materials," *Pure and Applied Chemistry* 79, no. 10 (2007): 1640, DOI: https://doi.org/10.1351/pac200779101635; Machiel J. Reinders, Marleen C. Onwezen, and Marieke J. G. Meeusen, "Can Bio-based Attributes Upgrade a Brand? How Partial and Full Use of Bio-based Materials Affects the Purchase Intention of Brands," *Journal of Cleaner Production* 162 (September 2017): 1170–73, DOI: https://doi.org/10.1016/j.jclepro.2017.06.126.

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23 Mironov et al., "Biofabrication," 1; Holt et al., "Fungal Mycelium and Cotton Plant Materials," 432; Ginsberg and Chieza, "Other Biological Futures"; R. J. J. Lelivelt et al., "The Production Process and Compressive Strength of Mycelium-Based Materials," in *Proceedings of the First International Conference on Bio-Based Building Materials* (Clermont-Ferrand, France, June 22–25, 2015), 1–3, available at https://pure.tue.nl/ws/files/15138585/leliproduct2015.pdf.

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We collected a total of $N = 60$ cases ranging from speculative installations by artists and designers to consumer products biodesign companies had developed. Our study excluded biological material applications for food, feeding, agriculture, pharmaceuticals, nutraceuticals, cosmetics, chemical alternatives, and environmental remediation.[92]

We clustered cases according to type of living organism—fungi, bacteria, or algae—and then analyzed the initial cases to identify ones for which the material was developed on an industrial scale. This selection process resulted in $N = 29$ cases of biodesign companies founded over the last fifteen years (Figure 4).

From those twenty-nine companies, we selected nine cases based on the following criteria: (a) the company has a portfolio of consumer products, such as accessories, apparel, or interior design applications; (b) the company describes the material/product; (c) the website has been updated recently (between October 2019 and June 2020). These criteria excluded companies such as Biomason,[93] which develops materials for the built environment; Ginkobioworks,[94] Colorifix,[95] and Pili,[96] which focus on developing dyes, but not on their application to everyday products; and Modern Meadow[97] and Glowee,[98] which do not describe their material/product in detail on their websites.

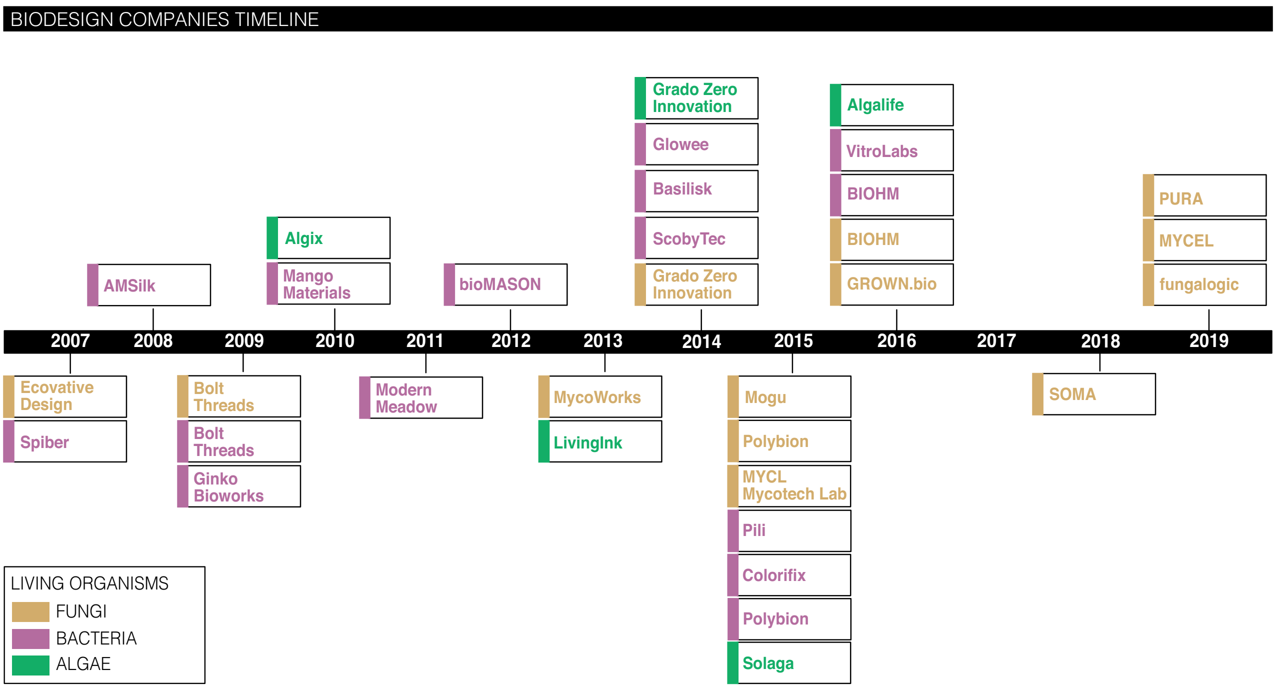


Figure 4
Timeline illustrating twenty-nine biodesign companies developing new materials from living organisms on an industrial scale.

BIODESIGN COMPANIES OVERVIEW

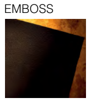
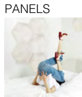
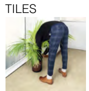
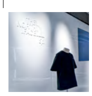
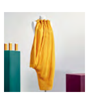
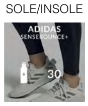
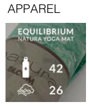
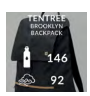
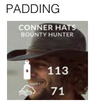
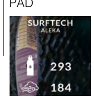
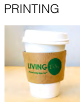
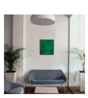
ORGANISMS	COMPANY	MATERIAL	APPLICATION	MATERIAL UPDATE
FUNGI	ECOVATIVE	MycoFlex™	INSULATING APPAREL  BACKPACK STRAPS  GLOVE LINER  FOOTWARE FOAMS  MAKE-UP SPONGES,...  SPA SLIPPERS,... 	
		MycoFlex™ x Mylo™	EX-PARTNERSHIP WITH BOLT THREADS FOR MYCELIUM TEXTILE APPLICATIONS (MYCELIUM LEATHER)	Forager™ Hides (2021) 
		Myco Composite™	PACKAGING  LAMPS & FURNITURE 'THE MUSH LUME HEMI PENDANT' GROWN.BIO (BY DANIELLE TROFE)  GIY KIT 	
	MYCOWORKS	Fine Mycelium™ to create Reishi™	REISHI BROWN NATURAL  REISHI BLACK EMBOSS 	
	MOGU	Mycelium composite	ACOUSTIC PANELS  FLOOR TILES 	
BACTERIA	SPIBER	Brewed Protein™	'MOON PARKA' THE NORTH FACE (BY GOLDWIN)  'CONCEPT BOARD' LOADED BOARDS & THE NORTH FACE (BY GOLDWIN)  'PLANETARY EQUILIBRIUM TEE' THE NORTH FACE  'COSMOS' AND 'BIRTH' COUTURE COLLECTIONS (BY YUIMA NAKAZATO) .  'LIMITED EDITION T-SHIRT COLLECTION (BY SACAI) 	
	AMSILK	Biosteel®	FUTURECRAFT BIOFABRIC SHOE (X ADIDAS) 	
	BOLT THREADS	B-Silk Protein™ to create Microsilk™	GOLD DRESS (X STELLA McCARTNEY)  BIOFABRIC TENNIS DRESS (X ADIDAS AND STELLA McCARTNEY) 	
ALGAE	ALGIX	BLOOM™ to create Rise EVA, Stride TPR	FOOTWARE SOLE/INSOLE  SPORT APPAREL  BACKPACK  HATS PADDING  SURF TRACTION PAD 	
	LIVING INK	Algae Ink™	INK FOR COFFEE SLEEVES AND COASTERS PRINTING  INK FOR PACKAGING, PAPER AND BUSINESS CARDS PRINTING  INK FOR OFFSET PRINTING 	
	SOLAGA	Algae Biofilm	PRIVATE INDOOR AIR FILTERING  PUBLIC INDOOR AIR FILTERING  OUTDOOR AIR FILTERING 	

Figure 5
Overview of nine biodesign companies selected for analysis, including materials and products applications.

We provide an overview of the selected cases according to type of organism and design applications in Figure 5. Table 1 presents these new companies, their website URLs, and their sub-brand websites and partnership websites. The selected companies produce other applications, such as food (Ecovative with fungi-based meat Atlast), medicine (AMSilk with Biosteel finishing treatment) and cosmetics (Bolt Threads with B-Silk Protein powder). We did not include these applications in our analysis.

Table 1 **The nine biodesign companies, their websites, partner websites, and sub-brand websites.**

Ecovative	http://www.ecovativedesign.com		
	Partners and ex-partners* licensing Ecovative's technology		
		Magical Mushroom MycoComposite	https://www.magicalmushroom.com/
		Paradise Packaging MycoComposite	https://www.paradisepackaging.co/
		Grown.bio MycoComposite and GIY Kit	https://www.grown.bio/
		Bolt Threads* MycoFlex × Mylo	https://boltthreads.com/technology/mylo/
Mycoworks	http://www.mycoworks.com		
	Mycoworks' sub-brand		
		Reishi leather	https://www.madewithreishi.com/
Mogu	http://www.mogu.bio		
Spiber	http://www.spiber.jp/en		
AMSilk	http://www.amsilk.com		
	AMSilk's sub-brand		
		Biosteel fiber	http://www.biosteel-fiber.com/home/
Bolt Threads	http://www.boltthreads.com		
Algix	https://algix.com/		
	Algix's sub-brand		
		Bloom foam	https://www.bloomtreadwell.com/
Living Ink	http://www.livingink.co/home-1		
Solaga	http://www.solaga.de		

Analysis

We monitored the biodesign companies' websites and collected textual and visual website data from October 2019 to June 2020. For each website, we produced a Word document categorizing the exact textual data according to each website's structure: page, title, subtitles, description, and so on. We also collected and archived images, schemas, graphics, video stills, and screenshots of website pages and external pages linked to the companies' websites. We conducted content analysis[99] to detect emergent clusters in textual and visual descriptions, extrapolating relevant paragraphs into a synoptic overview clustered by organism (for example, the fungi cluster). Each cluster was subdivided by company: the fungi cluster included Ecovative, Mycoworks, and Mogu, for example. For each company, we identified categories such as living organism, industrial process, material properties, material qualities, industrial applications, and company vision.

From these categories, we distinguished the data focusing specifically on the introduction or framing of the new material — the benefits of using a specific living organism in the industrial process, the qualities achieved in the resulting product, and more. We treated the visual data the same way, clustering them according to links and categories that emerged. We selected images that supported the texts or provided additional information, for example, about material outcomes or biofabrication processes, to include in our analysis.

In parallel, we conducted a word frequency analysis in each Word document using MaxQDA, a qualitative analysis software. Our goal was to identify organism-specific terms commonly used by all biodesign companies. We set a minimum word length of $N = 3$. We analyzed $N = 9$ documents, cleaned up redundant data — common words, conjunctions, company names, and so on — clustered single terms according to word roots, and reduced the initial total of 21,731 to 278 relevant words. Of the 278 relevant words, 61 were identified as organism-specific terms.

The authors discussed both content and frequency analysis in light of the theories presented above. The first author collected data from the companies' websites and identified the initial categories while conducting the first round of word frequency analysis. Then, the two authors discussed those categories and reached an agreement on each category's relevance and name (coding). To validate the analysis, the authors reached out informally to the Materials Experience Lab's biodesign experts. The authors also discussed the relationship between the extracted terms and the material clusters — in this case, $N = 61$ words: $n_{fungi\ cluster} = 27$ words; $n_{bacteria\ cluster} = 24$ words; $n_{algae\ cluster} = 10$ words — as well as the textual and visual analyses to further bolster the categories. The terms also helped articulate discussion points.

Results

Three Main Description Categories to Frame New Materials from Living Organisms

Our analysis revealed three main description categories: (a) material origins, (b) fabrication processes, and (c) material outcomes, which we present

25 Camere and Karana, "Fabricating Materials," 572–81.

26 Alexandra Daisy Ginsberg, "E. chromi: Living Colour from Bacteria," 2009, accessed April 19, 2021, http://www.daisyginsberg.com/work/echromi-living-colour-from-bacteria.

27 Montalti, "The Growing Lab"; Morby, "Ari Jónsson Uses Algae."

28 Clarke and Kitney, "Developing Synthetic Biology," 115–17.

29 Sachsenmeier, '"Industry 5.0," 226–28.

30 Rosalind A. Le Feuvre and Nigel S. Scrutton, "A Living Foundry for Synthetic Biological Materials: A Synthetic Biology Roadmap to New Advanced Materials," *Synthetic and Systems Biotechnology* 3, no. 2 (2018): 106, DOI: https://doi.org/10.1016/j.synbio.2018.04.002.

31 Merlin Sheldrake, *Entangled Life: How Fungi Make Our Worlds, Change Our Minds & Shape Our Futures* (New York: Random House, 2020).

32 Jordi F. Pelkmans, Luis G. Lugones, and Han A. B. Wösten, "15 Fruiting Body Formation in Basidiomycetes," in *Growth, Differentiation and Sexuality*, ed. Jürgen Wendland (Cham, Switzerland: Springer, 2016), 387–405, DOI: https://doi.org/10.1007/978-3-319-25844-7_15.

33 Since the companies that work with fungi use the mycelium growth to produce their products, in the analysis presented in the Results section we discuss "mycelium" instead of fungi.

34 Kevin Kavanagh, ed., *Fungi: Biology and Applications* (Wiley Online Library, 2005), 1–34; Muhammad Haneef et al., "Advanced Materials from Fungal Mycelium: Fabrication and Tuning of Physical Properties," *Scientific Reports* 7, no. 1 (2017): 41292, DOI: https://doi.org/10.1038/srep41292.

35 Elvin Karana et al., "When the Material Grows: A Case Study on Designing (with) Mycelium-Based Materials," *International Journal of Design* 12, no. 2 (2018): 121–23, http://www.ijdesign.org/index.php/IJDesign/article/view/2918/823.

36 Camere and Karana, "Growing Materials," 104; Camere and Karana, "Fabricating Materials," 573; Karana et al., "When the Material Grows," 121–23; Daniel Grimm and Han A.B. Wösten, "Mushroom Cultivation in the Circular Economy," *Applied Microbiology and Biotechnology* 102, no. 18 (2018): 7799, DOI: https://doi.org/10.1007/s00253-018-9226-8.

37 Taylor Burke, "Bolt Threads Partners with Adidas, Kering, Lululemon and Stella McCartney to Introduce Mylo™," *Business Wire*, October 2, 2020, https://www.businesswire.com/news/home/20201002005326/en/.

38 Wei-Cho Huang and I-Ching Tang, "Bacterial and Yeast Cultures — Process Characteristics, Products and Applications,"

below with examples. To present the findings and cross-case analysis in this section, we use quotes (and quotation marks) and keywords (in *italics*) scraped from the metadata of the companies' websites. Some of the websites have been updated since we concluded our analysis, and so we are not able to refer directly to them.

Material Origins

Most companies provide information about the living organism (the origin of the material) and its *raison d'être* in the natural ecosystem. These textual and visual descriptions explicitly refer to the original habitat in which each organism thrives.

In an earlier version of their website, Ecovative explains that "mycelium is the network of thread-like cells that make up fungi.… It holds the forest floor together and acts as nature's recycling system by releasing enzymes that break down natural materials and release nutrients into the soil."[100] Mycoworks explains that mycelium threads "form intricate, interlocking patterns that spread widely underground, branching and connecting, creating a vast mosaic that holds the world together."[101] Mogu indicates only that mycelium is the "the vegetative stage of mushrooms."[102] The three companies also use different visuals to represent the organism. Ecovative presents diagrams illustrating the mushroom and the hyphae as part of the ecosystem (Figure 6a). Mycoworks shows the company's founder Phil Ross holding the drawing of a mushroom.[103] Mogu displays a realistic image of a Petri dish containing a sample of mycelium (Figure 6b).

Companies that employ fermentation processes using bacteria (or yeast) often refer to the substances yielded by the fermentation process as *proteins*. Their introductions mention the organism's specific purpose as the production of proteins by activating the plant biomass sugar fermentation process[104] from which the final protein material is extracted.[105] The images Spiber and AMSilk use show biotech laboratories preparing for fermentation (Figures 7a, 7b). Only Bolt Threads includes a photograph of various patterns the living organism creates in Petri dishes (Figure 7c).

The firm Algix explains that algae are a biomass[106] whose exponential growth[107] can be extremely beneficial for different ecosystems.[108] In an earlier version of their website, Algix shows also a diagram detailing how algae "transform sunlight, water, and pollution … and … help the environment by cleaning and recirculating freshwater back into habitats."[109] In an earlier version of their website, Solaga calls algae the "ancestors of the plants … the oldest life forms on this planet … single-celled microorganisms that belong to the class of phototrophic organisms that perform photosynthesis.… As such, they can bind carbon dioxide with the help of light and thereby release oxygen"[110] and contribute to air pollution reduction.[111] Each company uses different visuals. Algix shows the location from which the algae are extracted (Figure 8a); Living Ink displays photos of algae under a microscope (Figure 8b); Solaga demonstrates algae samples cultivated in its laboratory (Figure 8c).

in *Bioprocessing for Value-Added Products from Renewable Resources*, ed. Shang-Tian Yang (Amsterdam: Elsevier, 2007), 186–89, DOI: https://doi.org/10.1016/B978-044452114-9/50009-8.

39 Like bacteria, yeast is widely used in fermentation processes. Yeasts are one-celled fungi, 5~10 μm in size. Yeast cells are usually spherical, cylindrical, or oval and important for their ability to ferment carbohydrates in various substances. Fermentation is a bioprocess of chemical reactions catalyzed by enzymes produced by bacteria, moulds, yeasts, and other microorganisms to produce value-added products from renewable resources. The results of this process (e.g., productivity, yield, and purity) are affected by the culture used (bacterial or yeast), physical and chemical factors, and operating conditions. Since these two types of organisms are interchangeably used in fermentation processes to obtain similar material outcomes, we consider them together as the "bacteria cluster."

40 S. W. Challinor and A. H. Rose, "Interrelationships between a Yeast and a Bacterium When Growing Together in Defined Medium," *Nature* 174, no. 4436 (1954): 877–78, DOI: https://doi.org/10.1038/174877b0.

41 Akira Shirata et al., "Isolation of Bacteria Producing Bluish-Purple Pigment and Use for Dyeing," *Japan Agricultural Research Quarterly* 34 (2000): 131, available at https://www.jircas.go.jp/sites/default/files/publication/jarq/34-2-131-140_0.pdf.

42 Goldwin × Spiber, "The Sweater," accessed May 3, 2021, https://www.goldwin-sports.com/us/feature/vq/.

43 M. Iguchi, S. Yamanaka, and A. Budhiono, "Bacterial Celullose — A Masterpiece of Nature's Arts," *Journal of Material Science* 35 (2000): 261–62, DOI: https://doi.org/10.1023/A:1004775229149; C. Dennis, "Breakdown of Cellulose by Yeast Species," *Microbiology* 71, no. 2 (1972): 409–10, DOI: https://doi.org/10.1099/00221287-71-2-409; Frankie M.C. Ng and Phoebe W. Wang, "Natural Self-Grown Fashion from Bacterial Cellulose: A Paradigm Shift Design Approach in Fashion Creation," *The Design Journal* 19, no. 6 (2016): 839–40, DOI: https://doi.org/10.1080/14606925.2016.1208388; Camere and Karana, "Fabricating Materials," 573–74.

44 Collet, "Designing Our Future Bio-materiality," 5.

45 "Living Colour," Laura Luchtman and Ilfa Siebenhaar, accessed May 11, 2021, https://livingcolour.eu/faq/.

46 "Design to Fade," Puma, accessed May 11, 2021, https://designtofade.puma.com/.

47 Khan et al., '"The Promising Future," 1.

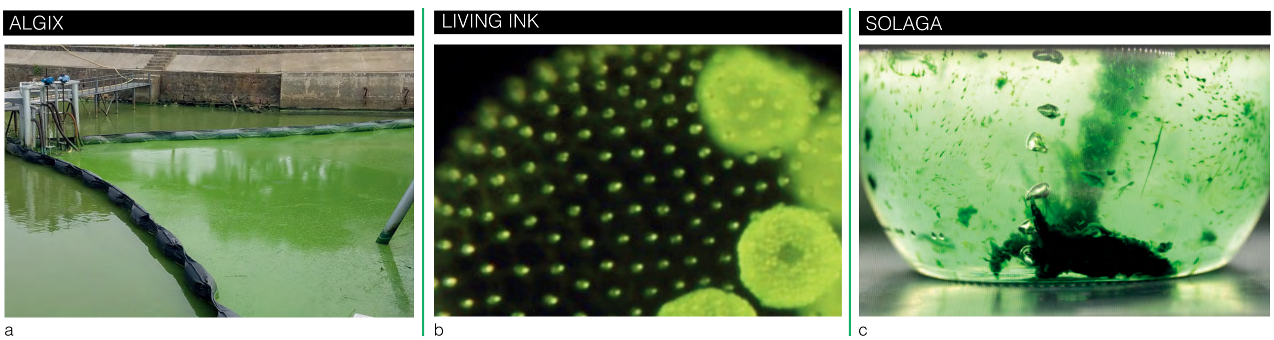


Figure 6 (top)
Visualizations of fungal mycelium. (a) **Ecovative**: Mycelium colony, mycelium life-cycle, and Hyphae presented in its Instruction Manual GIY Kit (p.11); (b) **Mogu**: Fungal Mycelium Technology.

Figure 7 (middle)
Visualizations of bacteria. (a) **Spiber**: small-scale microbial fermentation equipment in Spiber's laboratory; (b) **AMSilk**: production; (c) **Bolt Threads**: Mylo conceptual.

Figure 8 (bottom)
Visualizations of algae. (a) **Algix**: algae biomass; (b) **Living Ink**: microscopic algae; (c) **Solaga**: lab samples of algae.

(b) Fabrication Processes

All nine companies describe the potential of biofabrication for developing novel materials from living organisms. Their textual and visual descriptions mainly tap into the relationships between process and organism (what the organism contributes to a particular biofabrication process) and between process, organism, and material (how material outcomes can be finetuned due to the match between organism and process). They all extoll the cleaner production potential inherent in the transformation process.

Describing process-organism relations, Ecovative explains that biofabricating with mycelium requires little energy and few *resources*, and diminishes *pollution* and *waste*. Pictures and animations communicate how the organism *binds* strains and is placed in special industrial chambers to grow in molds (Figure 9a). A piece of mycelium packaging shows that the *growth* can be calibrated to define *thickness* and *rigidity* (Figure 9b). An operator holding a piece of mycelium foam in the air demonstrates the potential of mycelium to grow in *3D* strong *scaffoldings* (Figure 9c). Mycoworks boasts that mycelium is a source for creating a "manufacturing platform of natural material for a resilient future"[112] (Figure 9d). The company focuses on mycelium's potential to produce *leather*-like materials (Figure 9e) with various *densities and textures*. For Mogu, mycelium triggers *novel production paradigms* to develop *responsible products* where by-products get an *added value*. The company hints at this with a picture of cotton fibers used to feed the organism (Figure 9f). The composite's surface and the drawings show that mycelium can assume different *shapes*, *sizes*, *and textures* (Figure 9g).

Companies like Spiber, AMSilk, and Bolt Threads explain that *bacterial* cultures can be implanted in the *lab* with *modified DNA* sequences. The cultures feed on *plant feedstock* and turn them into *sugar*. By using sugar and *water* in a *fermentation process*, the organisms synthesize *unhydrolyzed proteins*. Once fermentation is completed, the proteins are *isolated* and *purified*, and the culture cells are *destroyed* with *heat*. Bolt Threads uses photos of scientists working in the lab (Figure 10e). Spiber and AMSilk share pictures of the bacterial cultures' continuous process of transformation into different materials (Figures 10a and 10d). To prove that, over time, materials derived from these proteins remain *sustainable*, *biocompatible* and *100% biodegradable*, AMSilk refers to its *ISO 9001* and *Trustworthy Textile* certifications. Spiber explains that bacterial cultures implanted with different DNA sequences can generate *different proteins* that can turn into *different materials* outputs, and displays the powder *protein material* with its original champagne-white color (Figure 10b). Spiber (Figure 10c) demonstrates that several *alternatives* to *petroleum or animal-derived raw materials* can be produced.

Algix explains that algae *biomass harvested* from *water* allows for the development of *algae-blend foams*. The process combines a content of 45% algae biomass with bio-based additives. When the biomass endures heat and pressure, it undergoes *plasticization*. The resulting substance can be processed into flakes, pellets, and powder, a suitable compound to produce sludge for the foam *extrusion process* (Figure 11a). Using algae makes the process more *sustainable* than when producing *EVA materials* (Figure 11b).

48 Martin Koller et al., "Characteristics and Potential of Micro Algal Cultivation Strategies: A Review," *Journal of Cleaner Production* 37 (December 2012): 377–78, DOI: https://doi.org/10.1016/j.jclepro.2012.07.044.

49 Jesús Ruiz et al., "Towards Industrial Products from Microalgae," *Energy & Environmental Science* 9, no. 10 (2016): 3036, DOI: https://doi.org/10.1039/C6EE01493C.

50 Scott Fulbright, "Is Algae the Ink of the Future? | TEDxMileHigh," YouTube video, 10:03, August 23, 2016, https://www.youtube.com/watch?v=4uAAeg-PkCKo&t=1s; "Textiles Produced from Algae," Sustainable Fashion. Earth, April 2, 2020, https://www.sustainablefashion.earth/type/recycling/textile-produced-from-algae/.

51 Qian Lu et al., "Application of a Novel Microalgae-Film Based Air Purifier to Improve Air Quality through Oxygen Production and Fine Particulates Removal," *Journal of Chemical Technology and Biotechnology* 94, no. 1 (2019): 1057–59, DOI: https://doi.org/10.1002/jctb.5852.

52 Arielle Pardes, "Slip into Earth-Friendly Running Shoes Made of Algae," Wired, accessed May 3, 2021, https://www.wired.com/story/slip-into-earth-friendly-running-shoes-made-of-algae/.

53 "Unconventional Trippen Footwear — Handmade in Germany," Trippen, accessed May 3, 2021, https://en.trippen.com/start.

54 Natashah Hitti, "Vollebak's Plant and Algae T-Shirt Becomes 'Worm Food' in 12 Weeks," *Deezen* (blog), August 28, 2019, https://www.dezeen.com/2019/08/28/vollebak-plant-and-algae-t-shirt-sustainable-biodegradable-fashion/; "Vollebak," https://www.vollebak.com/product/plant-and-algae-t-shirt/.

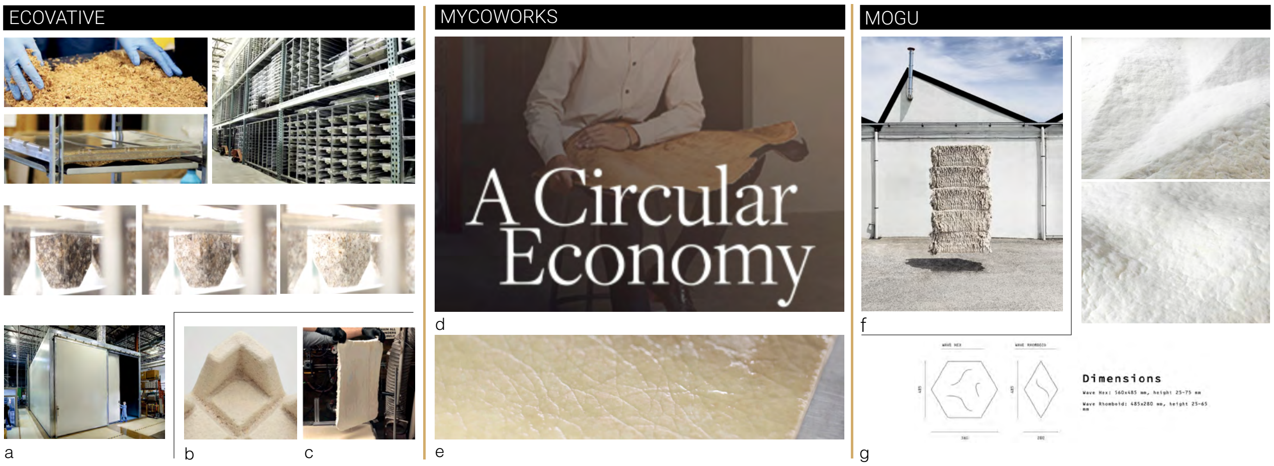
55 "Making Natural Upholstery Dye with Algae: Ikea's Virtual Greenhouse Project," Blond & Bieber, accessed April 19, 2021, https://blondandbieber.com/ikea-s-virtual-greenhouse-project.

56 Maine et al., '"Investing in New Materials," 16.

57 Eugene S. Stevens, *Green Plastics: An Introduction to the New Science of Biodegradable Plastics* (Princeton, NJ: Princeton University Press, 2002), 135–45.

58 Rognoli et al., "The Aesthetic of Interaction with Materials for Design."

59 Ezio Manzini and Antonio Petrillo, *Neolite: Metamorfosi Delle Plastiche* (Milano: Domus Academy, 1991), 16; Ezio Manzini and Giulio Castelli, *Artefatti: Verso Una Nuova Ecologia Dell'ambiente Artificiale* (Milano: Domus Academy, 1990), 17; Lore Veelaert et al., "The Identity of Recycled Plastics: A Vocabulary of Perception," *Sustainability* 12, no. 5 (2020): article no. 1953, 2, DOI: https://doi.org/10.3390/su12051953.



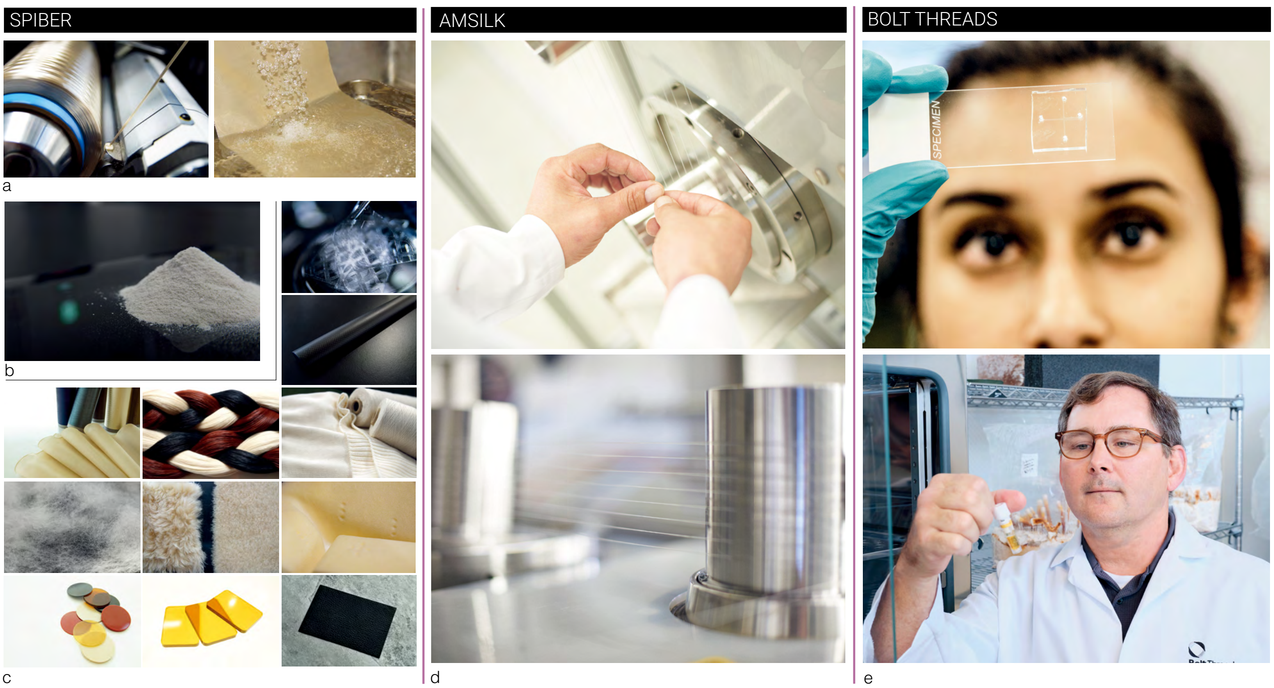


Figure 9 (top)
Visualizations of the potential of mycelium biofabrication. **Ecovative**: (a) the foundry: the magic process and growth chamber; (b) breakaway corner close up; (c) macro-structures; **Mycoworks**: (d) Fine Mycelium process by Mycoworks is an advanced manufacturing platform of natural materials for a resilient (and circular) future; (e) Fine Mycelium sheet; **Mogu**: (f) from textile waste to high-value products; (g) acoustic mycelium panels — Mogu Kite & Mogu Wave textures — and Mogu Wave's dimensions.

Figure 10 (bottom)
Visualizations of the potential of bacteria biofabrication. **Spiber**: (a) Brewed Protein powders processed into a continuous filament; Brewed Protein woven textile undergoing an experiment in which it is exposed to running water. Using this Brewed Protein material, designed at the molecular level to be hydrophobic, contraction is almost completely suppressed even after 30 minutes of testing. (b) Brewed Protein structural protein powder developed by Spiber. The properties of Brewed Protein materials can be customized to match the needs of the end user. (c) (Top to bottom; left to right): film created by processing Brewed Protein powder; composite material blending Brewed Protein with existing materials such as carbon fiber; filament and textile samples; artificial hair prototype made from Brewed Protein; spun yarn created by spinning with cotton. By changing the fiber diameter and protein content percentage, a variety of textures can be attained; Brewed Protein filament cut into short staple fibers; sample of material with a fur-like texture, made from processing Brewed Protein staple fibers; test sample of Brewed Protein added urethane foam material; resin created by processing Brewed Protein powder (round and rectangular shapes); experimental sample of leather-like material. **AMSilk**: (d) Biosteel. **BoltThreads**: (e) Bolt Lab Scientists.

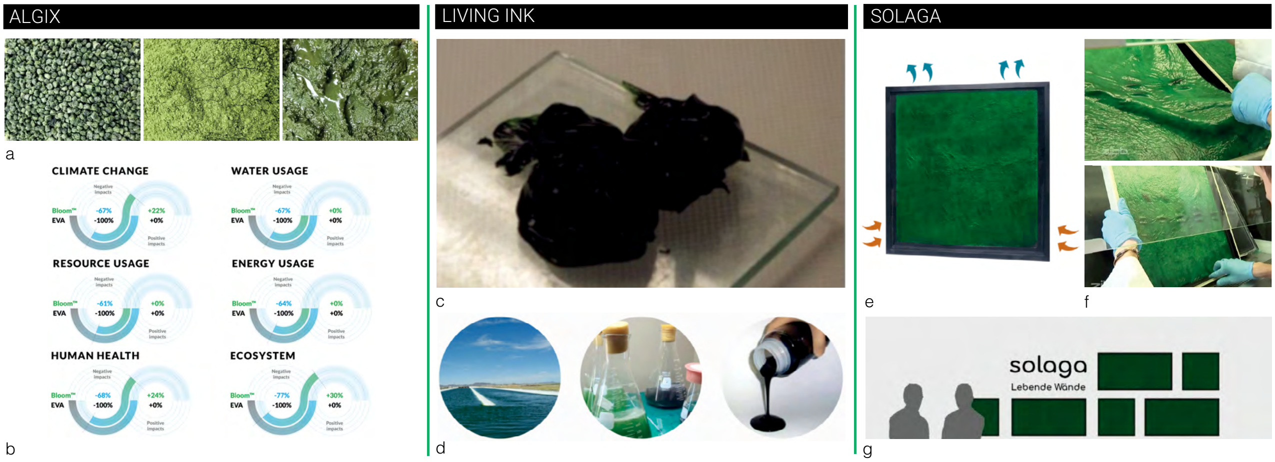


Figure 11
Visualizations of the potential of algae biofabrication. Algix: (a) sludge, powder, and pellet from algae biomass; (b) Life Cycle Assessment overview. Living Ink: (c) sample of ink pigment; (d) the three phases of the ink from algae obtention process. Solaga: (e) function diagram of biofilm filtering air; (f) transferring biofilm onto hard surface; (g) biofilm in various dimensions.

Living Ink explains that algae can *replace* production using *petroleum-derived pigments* (Figure 11c). Algae *grow* at a *large-scale* and contain a natural color *pigment* available for extraction and *purification*. After *milling*, the pigment can become a *dispersion, similar to carbon black* (Figure 11d). Solaga exploits algae's ability to *grow* in a *biofilm* that *binds* the *pollutants* present *in the air* (Figure 11e). *Under aseptic conditions*, algae can easily grow on a *surface*, creating a *protective skin layer* (biofilm) that can be then transferred onto a solid support (Figure 11f). The algae can grow this biofilm without dimensional constraints (Figure 11g).

Material Outcomes

Company descriptions of the material outcomes of biofabrication processes convey the new materials' potential forms, functions, and experiences, as well how they can be further processed to uncover new applications.[113] The descriptions also include aspects related to the recyclability, biodegradability, or composability of the resulting material.

For Ecovative (Figure 12), mycelium creates *next generation material* alternatives to plastics and leather. Mycelium-based materials are *strong*, *heat- and flame-resistant*,[114] *insulating*,[115] *biodegradable* and *home compostable*. As leather and foam, they are also *abrasion-resistant*[116] and *give padding*. A video shows a man hitting a MycoComposite block to demonstrate sturdiness. A feather on top of the material's surface hints at the *lightweight* and *breathability* of MycoFlex when transformed in leather (Mylo[117]). MycoFlex presents ball rebound, hydrophobic, and compression tests, along with a hand squeezing the material, and a white rabbit. A woman using a mycelium makeup sponge alludes to the protection it affords—it is *flexible*, *hypoallergenic*, and safe. The material is also *vegan* and *cruelty-free* and its consistency varies from tough to tender. The composite looks rough, the leather is described as *soft, supple and warm*, and the foam has a *velvet-soft surface*. Ecovative also mentions materials suitable for *everyday needs*. MycoComposite

60 Miodownik, "Toward Designing New Sensoaesthetic Materials"; Erik Tempelman, "Light Touch Matters. The Product Is the Interface," TUDelft, accessed April 19, 2021, https://www.tudelft.nl/en/ide/research/research-labs/emerging-materials-lab/lighttouchmatters; Siv Lindberg et al., "Hierarchic Design and Material Identity" (presented in the conference of Composites Week, Leuven, Belgium, September 16–20, 2013), available at https://www.researchgate.net/publication/301593204; Wilkes et al., "Design Tools."

61 Karana et al., "Material Driven Design," 39–40.

62 Roberto Verganti, *Design Driven Innovation: Changing the Rules of Competition by Radically Innovating What Things Mean* (Boston: Harvard Business Press, 2009).

63 Karana et al., "Material Driven Design," 39–40.

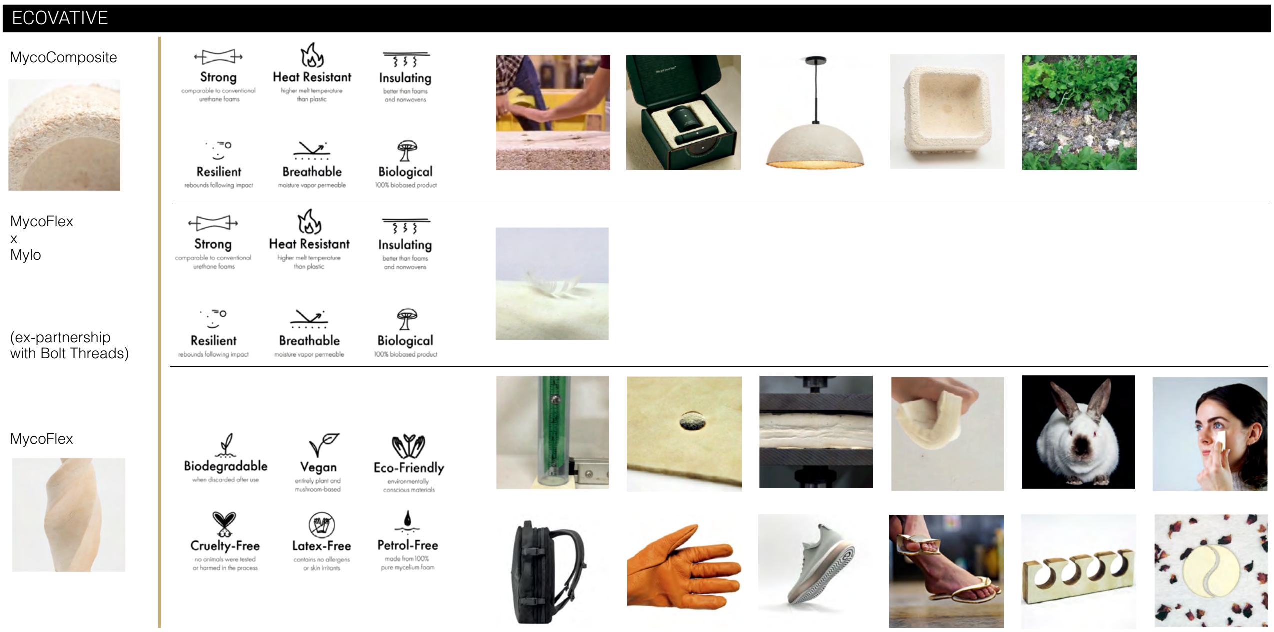
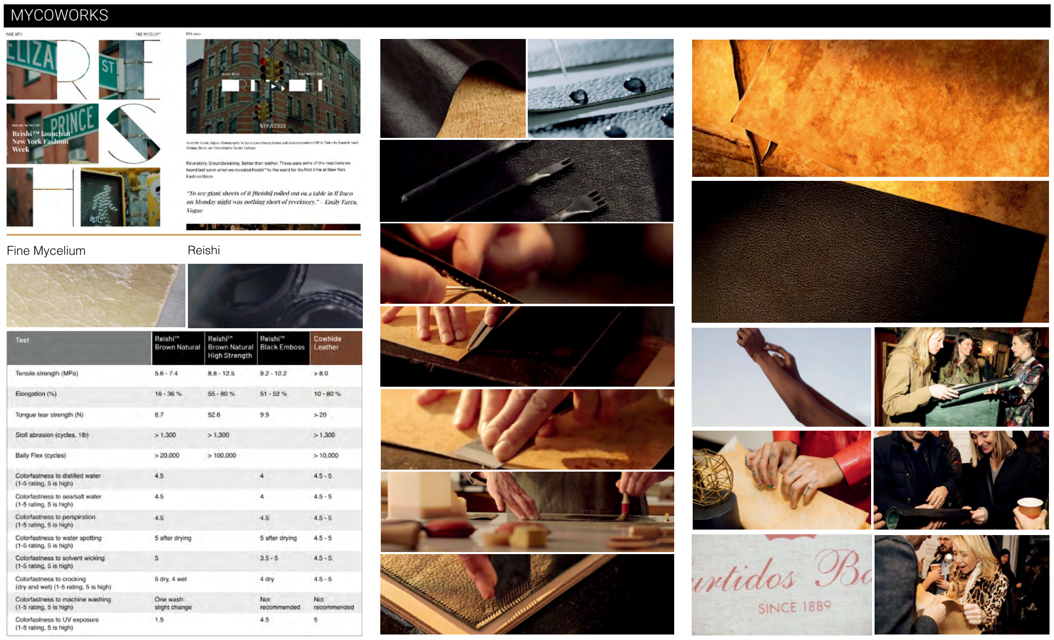


Figure 12
Ecovative's visualizations of the design potential of materials biofabricated from mycelium. (Left to right; top to bottom) MycoComposite: round planter close up, material properties, MycoComposite block (foreground), Seed welcome kit, Mush Lume hemi pendant, square planter, composted mycelium. MycoFlex × Mylo (ex-partnership): material properties, lightweight and breathability. MycoFlex: MycoFlex close up, material properties, rebound test, hydrophobic test, compression test, squeezing, hypoallergenic, safe, padding for backpack straps, glove liner, footwear, hygienic disposable products.

can take the archetypal *packaging* shape, and can also be used to make minimalistic furniture. MycoFlex transformed in leather (Mylo) can be utilized in fashion products. MycoFlex can contribute to *backpack straps*, *footwear*, and disposable products, for example.

Mycoworks (Figure 13) uses interviews with company founders, designers, and artisans to underline the potential of FineMycelium. The company presents a chart that shows mycelium leather surpassing animal leather performance[118] and visualizes the material's *flexibility* and *water wicking* properties with a hydrophobic test. With short videos and photographs, the company demonstrates that *leather working techniques*[119] and *tools* are adaptable to FineMycelium and that it comes in a *wide variety of colors*.[120] Mycoworks further describes FineMycelium as a *fine* material with a *gorgeous natural* (*matte*) *patina*. It is sensual and natural at the same time, comparable to human skin. It is *soft yet stiff and stable*, as hands exploring the material surface demonstrate. The company further highlights that FineMycelium is a material for *unprecedented* applications positioned between *tradition and innovation*, which people defined as *luxurious*, *high quality*, *revelatory*, and *ground-breaking* when viewing the Reishi collection during New York Fashion Week. Pictures from the event reveal the mesmerized reactions that the invitees have by looking and touching this leather that seems to come from the future.

Mogu (Figure 14) explains and illustrates that mycelium composite is *sound-dampening*, *fire-resistant*, *moisture proof*, *VOC-free*, *antistatic*, *lightweight*, *resistant to traction*, *easy to cut or tear apart*, *easy to spray paint*, *easy to glue and pierce*, and capable of *self-binding* to other materials. The also indicate that its high-density mycelium composite for flooring is resistant



Test	Reishi™ Brown Natural	Reishi™ Brown Natural High Strength	Reishi™ Black Emboss	Cowhide Leather
Tensile strength (MPa)	5.6 - 7.4	8.8 - 12.5	9.2 - 10.2	> 8.0
Elongation (%)	16 - 36 %	55 - 80 %	51 - 52 %	10 - 80 %
Tongue tear strength (N)	6.7	52.6	9.9	> 20
Stoll abrasion (cycles, 1lb)	> 1,300	> 1,300		> 1,300
Bally Flex (cycles)	> 20,000	> 100,000		> 10,000
Colorfastness to distilled water (1-5 rating, 5 is high)	4.5		4	4.5 - 5
Colorfastness to sea/salt water (1-5 rating, 5 is high)	4.5		4	4.5 - 5
Colorfastness to perspiration (1-5 rating, 5 is high)	4.5		4.5	4.5 - 5
Colorfastness to water spotting (1-5 rating, 5 is high)	5 after drying		5 after drying	4.5 - 5
Colorfastness to solvent wicking (1-5 rating, 5 is high)	5		3.5 - 5	4.5 - 5
Colorfastness to crocking (dry and wet) (1-5 rating, 5 is high)	5 dry, 4 wet		4 dry	4.5 - 5
Colorfastness to machine washing (1-5 rating, 5 is high)	One wash: slight change		Not recommended	Not recommended
Colorfastness to UV exposure (1-5 rating, 5 is high)	1.5		4.5	5

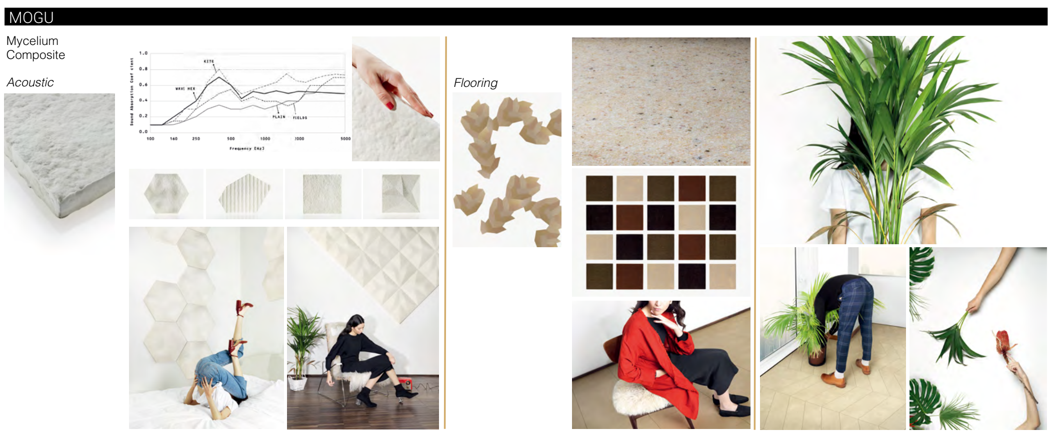


Figure 13 (top)
Mycoworks' visualizations of the design potential of materials biofabricated from mycelium. (Left to right; top to bottom) Landing page of Reishi's story "Reishi launch at New York Fashion Week"; fine Mycelium sheet; Reishi detail; table of Reishi's Vartest results; Reishi detail; test of Reishi's performance; leather working tools; hand stitching; edge scoring; edge skiving; gluing; in preparation for hand-stitching a pricking iron is used to mark the desired thread spacing; brown natural (regular and high strength) and black emboss ("Our Products"); Cover of Reishi's story "A new class of fine materials"; Erin Pollard, Summer Rayne Oakes, and Elettra Rossellini Wiedemann attend a private dinner for Reishi at Il Buco; visitors to Mycoworks' Elizabeth Street showroom; Curtidos Badia (since 1889) logo.

Figure 14 (bottom)
Mogu's visualizations of the design potential of materials biofabricated from mycelium. (Left to right; top to bottom) acoustic mycelium panels: Mogu plain detail, acoustic performance, texture, and touch; Mogu panels: wave, fields, plain, kite, Mogu wave interiors, Mogu kite interiors; resilient mycelium floors: oyster irregular shapes, oyster texture, oyster square tiles, oyster interiors.

under compression and colored with *biomasses*. Mogu describes mycelium's *candid surface* as having a *beautiful, natural white color* with *unique* and *captivating tone variations* that confer an *ethereal visual softness* with *distinctive tactile qualities*. When texturized, *visual patterns* create *playful contrast* with the soft surface. Figurative language likewise describes the aesthetics of the acoustic panels—"evoking the sensation of wandering through hills covered in fresh snow."[121] In its high-density form, the surface is *soft touch* and *matte* with a *fibered/non-fibered look*. The material receives praise as an *elegant*, *bold*, *radical*, and yet *unintrusive* solution in *interior design*, providing *comfort* by bringing "nature closer to people."[122]

Spiber (Figure 15) highlights that Brewed Protein materials are innovative and able to form textures, and that they feel like conventional materials without relying on *petrochemicals* or *animals*. Brewed Protein includes several varieties of protein polymers. Each polymer has different amino acid sequences with different characteristics and functions. This allows the material to meet the *quality* necessary for the products that Spiber is developing with partner companies. For instance, the textiles' *fibers can look like a silky shiny sheen*, have a *cashmere-like soft smoothness*, present a *wool-like, thermal*, *moisture-wicking surface*, but also resemble *tortoiseshell or animal horn* and *matte wool-like textiles*, and offer *superior levels of comfort*. These fibers can be combined with natural materials such as *cotton* (sacai Tee) and *bamboo fibers* (Concept Board). The company hints at the material's sustainable nature with the Planetary Equilibrium Tee, where a label reveals the potential of the t-shirt material to safely degrade in the ecosystem. Furthermore, the North Face's Moon Parka *outdoor jacket* and *garments* and *accessories* in Yuima Nakazato's Cosmos and Birth couture collections (Fall/Winter 2019 & Spring/Summer 2020) are modern and elegant products.

AMSilk (Figure 16) describes its Biosteel as a *bionic composite material* that is *strong*, *elastic* and *lightweight*, *resistant*, *non-immunogenic*, *non-inflammatory*, *non-toxic*, *biocompatible* and *extremely skin-friendly*, *vegan*, *100% biodegradable* and with perfect *moisture management* and *odor control*. The company states that a product built with Biosteel fiber, such as the Adidas Futurecraft Biofabric shoe, "can be reduced in weight by up to 30% in comparison to products made from common fibers,"[123] and that Biosteel is a *reliable* material because it was developed with German technology. This *silky* biopolymer is also *soft* and *smooth*. AMSilk conveys these concepts with inspirational pictures and simple graphics summarizing the material's applications in various product categories, including sports footwear, aerospace, automotive, and textiles.

Bolt Threads (Figure 17) claims its MicroSilk will *transform what we wear* and reconnect people to nature. Inspired by natural spider silk, an ancient material known for its tremendous *elasticity*, *lightness*, and *flexibility*. MicroSilk can be combined with other natural materials such as *cellulose blend fiber* (Biofabric Tennis Dress) and *wool* (Best Made Co.cap). The Biofabric Tennis Dress description emphasizes that this MicroSilk product is also *fully biodegradable*. Bolt Threads highlights that its *versatile biomaterial* possesses *remarkable properties* such as *softness* and can exhibit a *gold* shiny, smooth look (Stella McCartney Gold dress) or a white matte appearance

64 Elisa Giaccardi and Elvin Karana, "Foundations of Materials Experience: An Approach for HCI," in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (New York: ACM, 2015), 2451, DOI: https://doi.org/10.1145/2702123.2702337.

65 For more on the MDD method applied to a study of mycelium-based materials, see, for example, Karana et al., "When the Material Grows," 124–30.

66 Barati and Karana, "Affordances as Materials Potential," 113–18.

67 Dennis Chong and James N. Druckman, "Framing Theory," *Annual Review of Political Science* 10 (2007): 104–06, DOI: https://doi.org/10.1146/annurev.polisci.10.072805.103054; Dietram A. Scheufele, "Framing as a Theory of Media Effects," *Journal of Communication* 49, no. 1 (1999): 104–06, DOI: https://doi.org/10.1111/j.1460-2466.1999.tb02784.x; Kees Dorst, *Frame Innovation: Create New Thinking by Design* (Cambridge, MA: MIT Press, 2015), 53–55.

68 Everett M. Rogers, *Diffusion of Innovations*, 5th ed. (New York: The Free Press, 1995), 246–48.

69 Fred D. Davis, "A Technology Acceptance Model for Empirically Testing New End-User Information Systems: Theory and Results" (PhD dissertation, MIT, 1986), 24–26, http://hdl.handle.net/1721.1/15192.

70 Fred D. Davis, "Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology," *MIS Quarterly* 13, no. 3 (1989): 320, DOI: https://doi.org/10.2307/249008.

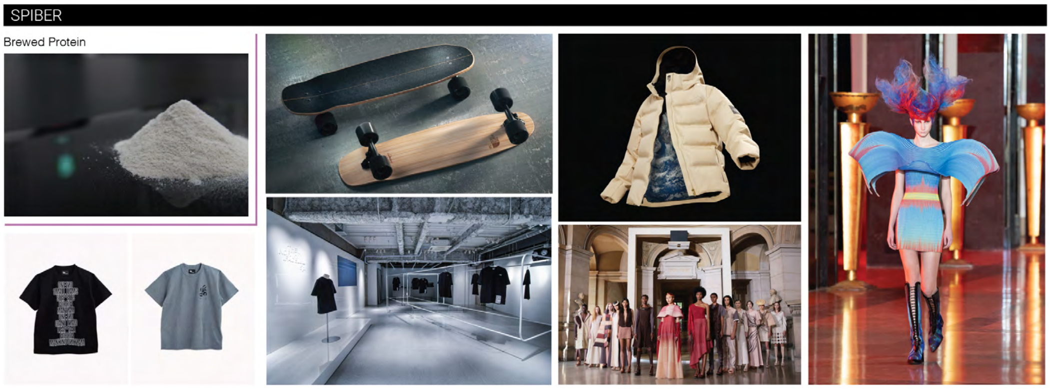
71 Diane Dormant, *The Chocolate Model of Change* (Lulu.com, 2011), 20.

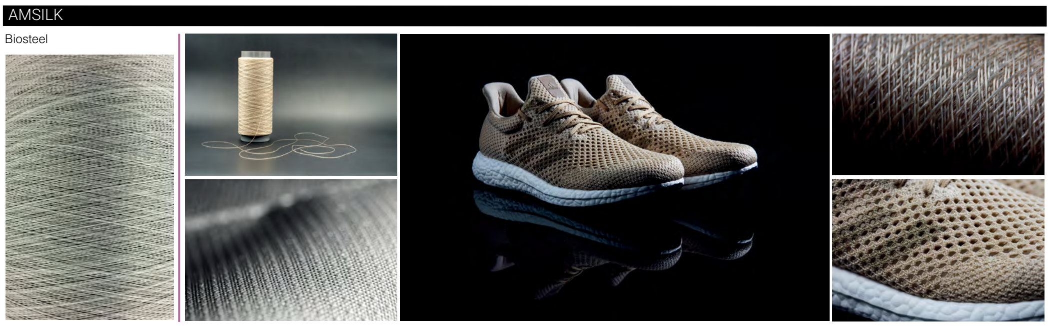
72 Rogers, *Diffusion of Innovations*, 107–13.

73 Nicholas Ind and Maria Chiara Riondino, "Branding on the Web: A Real Revolution?," *Journal of Brand Management* 9, no. 1 (2001): 13–14, DOI: https://doi.org/10.1057/palgrave.bm.2540048.

74 Jennifer Rowley, "Online Branding," *Online Information Review* 28, no. 2 (2004): 133, DOI: https://doi.org/10.1108/14684520410531637.

75 Kerry Smith and Dan Hanover, *Experiential Marketing: Secrets, Strategies, and Success Stories from the World's Greatest Brands* (Hoboken, NJ: Wiley, 2016), 63–98; Shih-Chih Chen and Chieh-Peng Lin, "Understanding the Effect of Social Media Marketing Activities: The Mediation of Social Identification, Perceived Value, and Satisfaction," *Technological Forecasting and Social Change* 140 (March 2019): 22–32, DOI: https://doi.org/10.1016/j.techfore.2018.11.025.





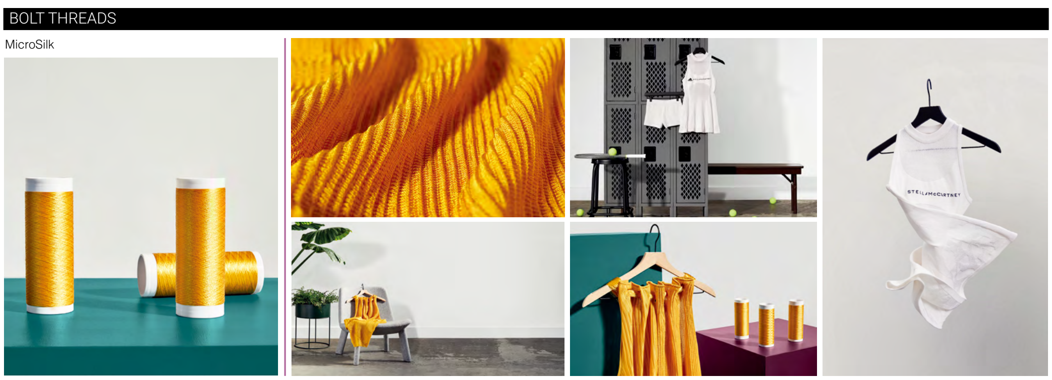


Figure 15 (top)
Spiber's visualizations of the design potential of materials biofabricated from bacteria. (Left to right; top to bottom) Brewed Protein structural protein powder developed by Spiber; sacai tee black (front) and sacai tee grey (front); a new material utilizing a bamboo (cellulose) core laminated with Brewed Protein textile; the North Face Alter store in Omotesando; the outwear jacket utilizing structural protein materials Moon Parka, a trademark of Spiber Inc. and Goldwin, Inc.; collaboration with fashion designer Yuima Nakazato, Paris Fashion Week Haute Couture Fall/Winter 2019 and Spring/Summer 2020.

Figure 16 (middle)
AMSilk's visualizations of the design potential of materials biofabricated from bacteria. (From left to right) Biosteel: wire, textile, Adidas Futurecraft Biofabric shoes, shoe fiber, shoe textile.

Figure 17 (bottom)
Bolt Threads' visualizations of the design potential of materials biofabricated from bacteria. (Left to right) Microsilk: spools of gold Microsilk, Gold MoMa dress close up, Gold MoMa dress lifestyle, Microsilk Tennis lifestyle, Microsilk Tennis dress.

(Biofabric Tennis dress). The products developed in collaboration with renowned brands and the company's Microsilk Tie demonstrate that the material has uses in both *luxury* and everyday products.

Algix (Figure 18) explains that algae foam is *flexible* and *highly rebounding* like *EVA* and *TPR foams*. It can then be *worked through standard processes* such as *sheet foaming*, *injection foaming*, and *compression molding*. The company samples provide visual proof of the softness, smoothness and color variety of the material. Furthermore, Algix provides data on the *environmental impact* that products made with algae-based foams can have. Algix supports this claim by showing *shoes* (H&M, Adidas), *accessories* (Conner, Tentree), and *sporting items* (Sea Lion Boards) made in collaboration with different companies. The samples display a modern material beneficial to consumers and the environment. The focus on creating circular materials is symbolically reflected in the company's infinite logo and its website's background images.

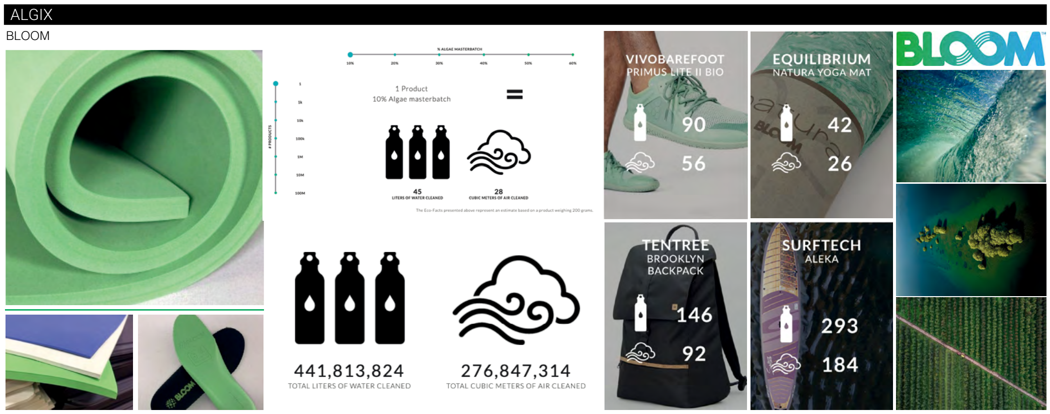
Living Ink (Figure 19) describes the *biopigment* it produces from algae as *resistant to UV-light exposure* and *safer* than petroleum-based ink. Algae pigment can be used in the same ways as other non-natural pigments *to formulate a wide variety of products* and can impart other tones than black, such as green and blue. Interesting applications with modern design aesthetics are shown by the company, such as *packaging* (Rocky Mountain Oils, Adidas), advertisement items (Patagonia Boulder *brochure*), and disposable items (*coasters* and *coffee sleeves*). These products remain 100% *sustainable* thanks to the use of biopigments.

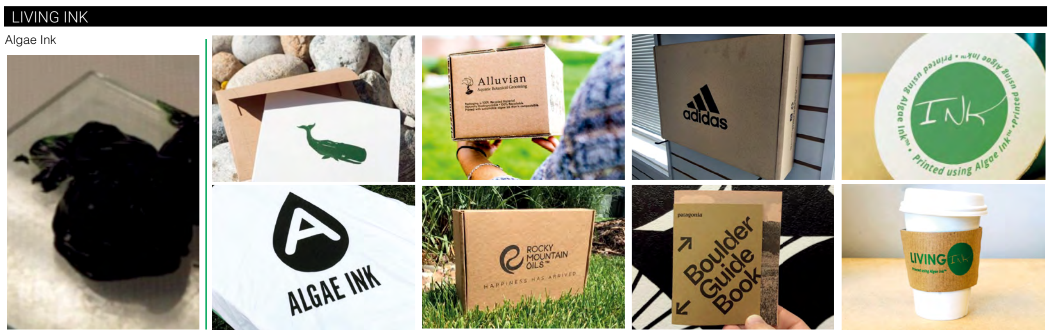
Solaga (Figure 20) considers algae-based materials to be the *natural solution* for *better* air. Algae biofilm *binds*, *deactivates*, and *consumes* air *pollutants*. To filter the air, the algae forming the biofilm need *water*, *air*, and *light* to *breathe*. At the end of its lifespan, the biofilm can be *disposed of* as *household waste*. The company emphasizes that algae biofilm is a *living material* whose *unique* aesthetic changes depending on surrounding *conditions*: in *shade* it goes *dark green* due to algae *accumulating pigments*, and in *direct sunlight* it turns *yellow* because algae *dismantle their photosystems*. The biofilm material can also be *laser-engraved* and cut as required. The Alwe wall decoration produced by Solaga, which contains the biofilm, is a great *eye-catcher* with a *modern* and *green* look that suits *home* and *office* contexts and *urban* landscapes that functions *silently* and *odorlessly*.

Cross-Case Analysis

Biodesign companies typically highlight their organisms' natural habitats, a practice that aligns with Machgeels'[124] proposal to include a material's origin in its narrative. However, while companies designing with algae visually portray the organisms in their natural habitat, emphasizing their roles in an ecosystem, bacteria- and fungi-related companies do not. Images of both mycelium-based materials' microscopic structure (hyphae) and the material substrate (mycelium) reveal pleasing aesthetics, contrary to the established, negative connotations that many associate with fungi. For bacteria-based materials, companies offer glimpses of the industrial environment where the living organisms transform into the material. This indicates that advance

76 Iñigo Gallo, Claudia Townsend, and Inés Alegre, "Experiential Product Framing and Its Influence on the Creation of Consumer Reviews," *Journal of Business Research* 98 (May 2019): 178, DOI: https://doi.org/10.1016/j.jbusres.2019.01.007.
77 Gallo et al., "Experiential Product Framing."
78 Jonathan Chapman, ed., *Routledge Handbook of Sustainable Product Design* (London: Routledge, 2017), 222–35.
79 Sylvia Machgeels, "Convivial Construct: A Method to Create Material Narratives to Positively Influence the Materials Experience" (Master's theses, Delft University of Technology, 2018), 140–60, http://resolver.tudelft.nl/uuid:19575905-5a0d-4841-9c32-9d925a0950a5.
80 Le Feuvre and Scrutton, "A Living Foundry," 111; Pedro F. Costa, "Translating Biofabrication to the Market," *Trends in Biotechnology* 37, no. 10 (2019): 1035, DOI: https://doi.org/10.1016/j.tibtech.2019.04.013.
81 Camere and Karana, "Fabricating Materials," 578–79; Karana et al., "When the Material Grows," 131.
82 "Biotours," Ceneic, accessed April 19, 2021, http://www.ceneic.co.uk/biotours/.
83 "Biotours at DDW," Dutch Design Week, accessed April 19, 2021, https://ddw.nl/en/programme/3124/biotours-at-ddw.
84 These keywords included: biomaterials, fungi, mycelium-based materials, fungal materials, bacteria, bacteria-based materials, algae, algae-based materials, algal materials, growing design, living materials, biofabricated materials.
85 Bader et al., "Grown, Printed, and Biologically Augmented," 79; Camere and Karana, "Growing Materials," 102; Camere and Karana, "Fabricating Materials," 573; Anaïs Moisy and Larissa Pschetz, "Designing with Living Organisms," in *Proceedings of the 3rd Biennial Research through Design Conference* (Edinburgh, UK, March 22–24, 2017), 323–39, DOI: https://doi.org/10.6084/m9.figshare.4746994.
86 Neri Oxman, "Design at the Intersection of Technology and Biology," TED video, 17:23, filmed March 2015, https://www.ted.com/talks/neri_oxman_design_at_the_intersection_of_technology_and_biology.
87 Ginsberg et al., *Synthetic Aesthetics*.
88 "Deezen," accessed May 11, 2021, https://www.dezeen.com/; "DesignBoom," accessed May 11, 2021, https://www.designboom.com/; "Core77," accessed May 11, 2021, https://www.core77.com/.
89 "Wired," accessed May 11, 2021, https://www.wired.com/; "Bloomberg," accessed May 11, 2021, https://www.bloomberg.com/europe.
90 "Biodesign. On the Cross-Pollination of Nature, Science and Creativity," Het Nieuwe Instituut, accessed April 19, 2021, https://biodesign-online.hetnieuweinstituut.nl/en.





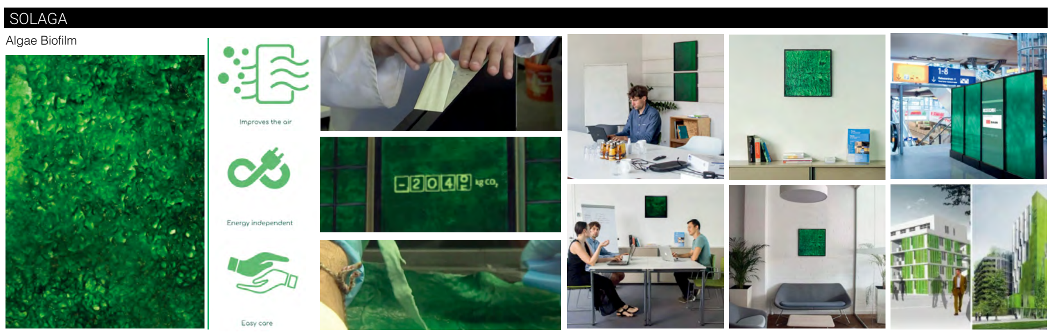


Figure 18 (top)
Algix's visualizations of the design potential of materials biofabricated from algae. (Left to right; top to bottom) large Bloom foam sheet; colored Bloom foam sheets; compression-molded EVA insoles (Rise); estimated eco-facts based on a product weighing 200 grams; total liters of clean water + total liters of clean air (clean water + clean air certification); examples of brand allies partnering with Bloom to clean water and air with every product; Bloom infinite logo; nature-and water-inspired background landscapes.

Figure 19 (middle)
Living Ink's visualizations of the design potential of materials biofabricated from algae. (Left to right) sample of Algae Ink pigment; offset and packaging printing for various brands on several types of paper differentiated by thickness and color background.

Figure 20 (bottom)
Solaga's visualizations of the design potential of materials biofabricated from algae. (Left to right; top to bottom) detail of algae biofilm; diagram highlighting biofilm's potential indoor and outdoor uses; detail of biofilm encasing with slot to allow the air to flow; laser-engraved biofilm; detail of algae biofilm cut with scissors; algae biofilm used in Alwe indoor and outdoor decor in different contexts.

91 Biofabricate, "Biofabricate Summit 2019"; Collet, "Alive: New Design Frontiers"; Montalti, "Fungal Futures."
92 "The Ket Maps," KindEarth.Tech, accessed April 19, 2021, https://newprotein.org/.
93 "BioMason," accessed April 25, 2021, https://www.biomason.com/.
94 "GinkoBioworks," accessed April 25, 2021, https://www.ginkgobioworks.com/.
95 "Colorifix," accessed April 25, 2021, https://colorifix.com/.
96 "Pili," accessed April 25, 2021, https://www.pili.bio/.

processing is required when making materials out of bacteria and yeast, but the companies hardly mention *bacteria* as an organism.

In Figure 21, we present the terms we extracted from the companies' textual material framings to summarize the differences and similarities among the three materials ($N = 61$ words; $n_{fungi\ cluster} = 27$ words; $n_{bacteria\ cluster} = 24$ words; $n_{algae\ cluster} = 10$ words). All the companies frame their materials as *new* and *sustainable*, and emphasize their future mindedness with terms such as *next generation*, *advanced*, and *breakthrough*. Although *growth* is a natural phenomenon common to all living things,[125] we found that companies developing mycelium-based materials use the term *grown materials* more frequently than those using bacteria and algae, stressing the organism's design potential plus the fabrication process. The visual elements the companies choose highlight the differences in each biofabrication process. Companies working with mycelium-based materials frame biofabrication as a series of actions an operator undertakes in response to the organism's development. Companies working with bacteria frame the process as dynamic yet controlled, achieved through carefully combining ingredients in different proportions. Companies manipulating algae frame the process with greater emphasis on clean production and circularity than the other companies.

When it comes to the materials' design potential,[126] the companies using mycelium communicate the material's crafted (*fine*, *functional*, *versatile*)

Figure 21
Commonly used terms (N = 61 words) to define fungi- ($n_{fungi\ cluster}$ = 27 words), bacteria- ($n_{bacteria\ cluster}$ = 24 words), and algae-based materials ($n_{algae\ cluster}$ = 10 words), ordered alphabetically among material categories. Similar terms among two material categories indicated with *; similar terms across all three material categories indicated with **.

FUNGI	BACTERIA	ALGAE
advanced materials *	advanced materials *	age-old materials
alternative to plastic-based materials	amazing materials	algae-based materials
better materials*	better materials*	breathing materials
biomaterials*	bio-based materials	innovative materials
breakthrough materials	biodegradable materials	living materials*
compostable materials	bioderived materials	material change
conscious materials	biomaterials*	material innovation
contrast to plastic-based materials	bionic composite materials	new materials**
crafted materials	customisable materials	sustainable materials**
durable materials	credible materials	useful materials
earth-friendly materials	fascinating materials	
fine materials	high-performance materials	
functional materials	new materials**	
grow-it-yourself materials	next generation materials*	
grown materials	next generation composite materials	
living materials*	next material revolution	
mushroom materials	protein biomaterials	
mycelium-based materials	protein materials	
mycelium	protein-based materials	
natural materials	sugar and microbes-derived materials	
new material category	sugar and microbes-produced materials	
new materials **	sustainable created materials	
next generation materials*	sustainable materials**	
raw materials	unique materials	
sustainable materials**		
versatile materials		
100% vegan composite materials		

and earth-friendly (*sustainable*, *vegan*) aspects in everyday use as a design statement. Companies transforming bacteria used *bionic composite materials* and *customizable materials* to emphasize the material's ability to mimic other materials and assume different forms. To frame algae-based materials, we see the terms *living* and breathing used to capture the algae's livingness[127] and capacity to photosynthesize when the organism is kept alive in the final material.

Discussion and Future Research

We firmly believe that by improving knowledge and skills for introducing new materials to consumer markets, biodesign companies will evolve their ability to shorten the uptake period of innovative materials from living organisms and cultivate widespread acceptance. In this article, foregrounding materials framing as an essential step in biodesign, we present how biodesign companies currently frame new materials generated from living organisms and how these frames vary depending on the organism. We identify three main categories—*material origins*, *fabrication processes*, and *material outcomes*—as means to operationalize materials framing thinking in biodesign. In this final section, we present the key concepts from our findings that require attention in future biodesign research and practice.

Communicating Organism's Design Potential

The three categories that emerged during our analysis reveal that biodesign companies communicate a material's origin as a living organism, the potential benefits of biofabrication for producing clean materials with unique functions, and the design potential of materials created using biofabrication. While all the companies foreground these three categories in their materials framing, there are notable variations in the ways they highlight "livingness" as a unique aspect of the materials' development. We argue that specifically communicating the potential represented by an organism's livingness[128]—its design potential—is unique to the field of biodesign and central to appropriately framing new materials from living organisms. Livingness entails what the organism affords in its natural habitat (Mycoworks explains that mycelium is a resource that shapes and structures nature, for example), the manmade habitat during design (Spiber shows the opportunities that may arise during bacteria fermentation), and in use (Solaga states that changes in an algae biofilm surfaces indicate biofilm activity in response to shifting surroundings). These frames draw attention away from a (typically) unidirectional focus on *material outcomes*. Instead, they offer "the organism" and its "livingness" as lenses to frame the materials, which can ultimately enhance our appreciation of them and promote their seamless integration into our daily lives. We aim to explore this premise in future work.

Need for a Biodesign Lexicon

Overall, there are significant discrepancies in the ways companies, scholars, and practitioners describe biofabrication processes and material outcomes. For instance, companies working with fungi use the terms fungi,[129] fungal

97 The Modern Meadow website was updated with details on the process, material, and product outcomes after conclusion of the study. For more information, visit https://www.modernmeadow.com/.
98 "Glowee," accessed April 25, 2021, https://www.glowee.com/.
99 Klaus Krippendorff, *Content Analysis: An Introduction to Its Methodology* (Thousand Oaks, CA: Sage, 2018), 18.
100 At the time of analysis, Ecovative presented Mylo as a material developed in partnership with Bolt Threads. This quote was taken from the Bolt Threads website during initial data collection. The quote cannot be found on the current version of the website. The raw data can be provided by authors upon request.
101 Made with Reishi, "A New Class of Fine Material—Reishi™," accessed May 3, 2021, https://www.madewithreishi.com/stories/a-new-class-of-fine-material.
102 Mogu, "Mycelium," accessed April 19, 2021, https://mogu.bio/technology/.
103 The authors were unable to obtain the image reprinting permission from the company. The referred image can be found at Made with Reishi, "A Story of Nature, Art and Science," accessed May 19, 2021, https://www.madewithreishi.com/stories/our-heritage.
104 Spiber, "Brewed Protein™," accessed May 13, 2021, https://www.spiber.inc/en/brewedprotein/.
105 Bolt Threads, diagram illustrating "Bolt Technology—Meet MicroSilk™," accessed May 13, 2021, https://boltthreads.com/technology/microsilk/.
106 Bloom, "Rise," accessed May 3, 2021, https://www.bloomtreadwell.com/rise/. Algix's website dedicated to the material brand Bloom.
107 Bloom, "Clean Water," accessed May 13, 2021, https://www.bloommaterials.com/. Algix's website dedicated to the material brand Bloom.
108 Bloom, "Why Does Rise Contain Algae?," accessed May 13, 2021, https://www.bloommaterials.com/rise/. Algix's website dedicated to the material brand Bloom.
109 This quote was taken from a diagram presented in a previous version of the website: https://www.bloomtreadwell.com/. The quote cannot be found in the current version of the website. The raw data can be provided by authors upon request.
110 These quotes were found on the FAQ section presented on a previous version of the company website (https://www.solaga.de/alwe/) and translated in English. The quotes cannot be found in the current version of the website. The raw data can be provided by authors upon request.

materials, fungal mycelium,[130] mycelium,[131] and mycelium-based materials[132] interchangeably. Some companies refer to their products as "living material," even though the final outcome is inert (with the exception of Solaga's algae biofilms). Finding terms to describe materials from living organisms that resonate with the public is challenging. Our research also showed that new terms—*inoculum*, *fermentation*, *sterilization*, and *incubation*—have penetrated design. In a recent presentation of Mylo, Bolt Threads introduced its Bolt Glossary and Mylo lexicon, which includes terminology to describe their new materials.[133] Their gesture reveals an overarching need for a microbial lexicon for biodesign that embraces and communicates the experimental aspects of this emerging design practice, the organisms' potential, plus possible material outcomes.

Digital Tools to Communicate Unique Material Qualities

Capturing the unique qualities of new materials, particularly ones that are alive and may change over time, is challenging. Biodesign companies rely on conventional means to present the experiential qualities of their materials: photographs of users experiencing materials for the first time or animated images demonstrating a material's response to touch, for example. Developing new tools that support digital storytelling[134] and communication of these novel materials' stories to the public in immersive experiences requires further research.[135]

Although the data presented in this article focus on framings of new materials generated from living organisms, we see the potential to further explore materials framing in relation to other types of novel materials whose origins, processes, and outcomes are essential to establishing widespread, shared understanding and, eventually, acceptance.

Conclusion

This article contains an extensive review of the textual and visual content of websites of nine biodesign companies that design everyday products to be made with fungi, bacteria, and algae. In our review, we have identified three categories that can help companies frame novel materials and highlight their ongoing development potential: *material origins*, *fabrication processes*, and *material outcomes*. Based on our insights, opportunities for future research might include conceptualizing a new microbial lexicon to further communicate the organisms' potential in biodesign and developing new digital support tools to communicate the unique qualities of novel materials made from living organisms.

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111 Solaga, "How Does Alwe Improve Air Quality?," accessed May 13 2021, https://www.solaga.de/alwe/. Translated from German to English.
112 Made with Reishi, "A Story of Nature, Art and Science," accessed May 3, 2021, https://www.madewithreishi.com/stories/our-heritage. Mycoworks' website dedicated to the material brand Reishi.
113 Giaccardi and Karana, "Foundations of Materials Experience," 2449–51; Barati and Karana, "Affordances as Materials Potential," 108–13.
114 For example, higher melt temperature than plastic.
115 For example, R-Value of 4 better than petroleum foams and nonwovens.
116 For example, like urethane foams and cowhide leather.
117 At the time of analysis, Ecovative presented Mylo as a material developed in partnership with Bolt Threads. The partnership between Ecovative and Bolt Threads was dissolved at some point after the conclusion of our study.
118 Tensile strength (Mycelium: 10 MPa/ Cowhide average: 8+ MPa), abrasion resistance (Mycelium: 100,000+ flexing cycles/ Cowhide average: 100,000+ flexing cycles) and color fastness (Mycelium: 4-5 out of 5/ Cowhide average: 4.5 out of 5).
119 These techniques included skiving, pricking, hand-stitching, edge painting, embossing, dyeing, sewing, pressing, heating, gluing, and beeswaxing.
120 A golden-tan called "brown natural" and the black tone named "black emboss" are included in the last company collection called Reishi.
121 Mogu, "Mogu Wave," accessed May 3, 2021, https://mogu.bio/acoustic/mogu-wave/.
122 Mogu, "Closer to Nature," accessed May 3, 2021, https://mogu.bio/about/.
123 AMSilk, "The Biosteel® Story—Fascinating by Nature," accessed May 3, 2021, http://www.biosteel-fiber.com/home/. AMSilk'S website dedicated to the material brand Biosteel.
124 Machgeels, "Convivial Construct."
125 Karana et al., "When the Material Grows," 121–23.
126 Barati and Karana, "Affordances as Materials Potential," 108–13.
127 Elvin Karana, Bahareh Barati, and Elisa Giaccardi, "Living Artefacts: Conceptualizing Livingness as a Material Quality in Everyday Artefacts," *International Journal of Design* 14, no. 3 (2020): 37–53, http://www.ijdesign.org/index.php/IJDesign/article/view/3957; Elvin Karana, *Still Alive: Livingness as a Material Quality in Design* (Breda, Netherland: Avans University of Applied Sciences, 2020).

128 Karana, "Still Alive," 7–10; Karana et al., "Living Artefacts," 1.
129 Camere and Karana, "Fabricating Materials," 573–74.
130 Montalti, "Fungal Futures"; Haneef et al., "Advanced Materials from Fungal Mycelium," 2; Holt et al., "Fungal Mycelium and Cotton Plant Materials," 1–2.
131 Camere and Karana, "Fabricating Materials," 571–72.
132 Karana et al., "When the Material Grows," 121–23; Lelivelt et al., "The Production Process," 1–2; Appels et al., "Fabrication Factors Influencing Mechanical," 65.
133 "The Bolt Glossary," Bolt Threads, accessed April 19, 2021, https://lnkd.in/gJmiQa8.
134 Ivan Sanchez-Lopez, Amor Perez-Rodriguez, and Manuel Fandos-Igado, "The Explosion of Digital Storytelling. Creator's Perspective and Creative Processes on New Narrative Forms," *Heliyon* 6, no. 9 (2020): e04809, DOI: https://doi.org/10.1016/j.heliyon.2020.e04809.
135 Sarah Lugthart, Michel van Dartel and Annemarie Quispel, "Plans Versus Situated Actions in Immersive Storytelling Practices," in *International Conference on Interactive Digital Storytelling* (Cham, Switzerland: Springer, 2017), 39–40, DOI: https://doi.org/10.1007/978-3-319-71027-3_4.

Declaration of Interests

There are no conflicts of interest involved in this article.

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Appendix The full original figure captions

Figure 1 (a) Mylo™ vegan leather from fungal mycelium; (b) limited release Mylo Driver Bag (in black) made in collaboration with Chester Wallace. Images courtesy of Bolt Threads.

Figure 2 (a) Living Colour; (b) PUMA × Living Colour: Design to Fade. Images courtesy of Laura Luchtman and Ilfa Siebenhaar, photography by Ingo Foertsch.

Figure 3 (a) Studio Blond & Bieber × Ikea Virtual greenhouse, Dutch Design Week, 2020: still taken from video shot by Dominick Backhaus, 2020, available at Ikea, “Making Natural Upholstery Dye with Algae,” YouTube video, still located at 5:25, 7:34, October 18, 2020, https://www.youtube.com/watch?v=HDyK6AodXZY; (b) Studio Blond & Bieber, Algaemy Bench No. 1. Image courtesy of Blond & Bieber, photography by Rasa Weber.

Figure 4 Timeline illustrating twenty-nine biodesign companies developing new materials from living organisms on an industrial scale. © 2021 Patrizia D’Olivo and Elvin Karana.

Figure 5 Overview of nine biodesign companies selected for analysis, including materials and products applications. Images courtesy of Ecovative, Mycoworks, Mogu, Spiber, AMSilk, Bolt Threads, Algix LLC, Living Ink, Solaga. (Notes to Figure) MycoFlex™ × Mylo: ex-partnership between Ecovative and Bolt Threads. At the time of analysis, Ecovative presented Mylo as a mycelium leather-like material developed in partnership with Bolt Threads through aerial growth technology (Air™ Mycelium) applied to MycoFlex. The partnership between Ecovative and Bolt Threads ended, and the license became non-exclusive. Currently, Ecovative is continuing to develop Forager™ Hides pre-tanned mycelium hides that tanneries can “plug and play” into their existing tanning process. Bolt Threads is continuing the development of Mylo in consortium with Adidas, Lululemon, Stella McCartney, and Kering. The Mush Lume hemi pendant (“Lamps & Furniture”): image courtesy of Grown.bio × Ecovative, design and photography by Danielle Trofe (2020, NY).

Figure 6 Visualizations of fungal mycelium. (a) Ecovative: Mycelium colony, mycelium life-cycle, and Hyphae presented in its Instruction Manual GIY Kit (p.11); (b) Mogu: Fungal Mycelium Technology. Images courtesy of Ecovative and Mogu, respectively.

Figure 7 Visualizations of bacteria. (a) Spiber: small-scale microbial fermentation equipment located in the laboratory at Spiber’s headquarters; (b) AMSilk: production; (c) Bolt Threads: Mylo conceptual. Images courtesy of Spiber Inc., AMSilk, and Bolt Threads, respectively.

Figure 8 Visualizations of algae. (a) Algix: algae biomass; (b) Living Ink: microscopic algae; (c) Solaga: lab samples of algae. Images courtesy of Algix, LLC, Living Ink, and Solaga, respectively.

Figure 9 Visualizations of the potential of mycelium biofabrication. Ecovative: (a) the foundry: the magic process (stills taken from animation available at https://www.grown.bio/about-grown/) and growth chamber; (b) breakaway corner close up; (c) macrostructures (still taken from animation (no longer available), Ecovative; raw data available from authors upon request). Images courtesy of Grown.bio × Ecovative and Ecovative. Mycoworks: (d) Fine Mycelium™ process by Mycoworks is an advanced manufacturing platform of natural materials for a resilient (and circular) future; (e) Fine Mycelium sheet. Images courtesy of Mycoworks and www.madewithreishi.com @mycoworks @madewithreishi. Mogu: (f) from textile waste to high-value products; (g) acoustic mycelium panels — Mogu Kite & Mogu Wave textures — and Mogu Wave’s dimensions. Images courtesy of Mogu.

Figure 10 Visualizations of the potential of bacteria biofabrication. Spiber: (a) Brewed Protein™ powders processed into a continuous filament; Brewed Protein woven textile undergoing an experiment in which it is exposed to running water. Using this Brewed Protein material, designed at the molecular level to be hydrophobic, contraction is almost completely suppressed even after 30 minutes of testing. (b) Brewed Protein structural protein powder developed by Spiber. The properties of Brewed Protein materials can be customized to match the needs of the end user. (c) (Top to bottom; left to right): film created by processing Brewed Protein powder; composite material blending Brewed Protein with existing materials such as carbon fiber. Materials like those in this impact beam prototype can be used in light, shock-absorbing automotive parts; filament and textile samples; artificial hair prototype made from Brewed Protein, developed in collaboration with Aderans Co., Ltd.; spun yarn created by spinning with cotton. By changing the fiber diameter and protein content percentage, a variety of textures can be attained; Brewed Protein filament cut into short staple fibers; sample of material with a fur-like texture, made from processing Brewed Protein staple fibers; test sample of Brewed Protein added urethane foam material; resin created by processing Brewed Protein powder (round and rectangular shapes); experimental sample of leather-like material. Images courtesy of Spiber Inc. AMSilk: (d) Biosteel®. Image courtesy of AMSilk. Bolt Threads: (e) Bolt Lab Scientists. Image courtesy of Bolt Threads.

Figure 11 Visualizations of the potential of algae biofabrication. Algix: (a) sludge, powder, and pellet from algae biomass; (b) Life Cycle Assessment (LCA) overview. Images courtesy of Algix, LLC. Living Ink: (c) sample of ink pigment (available at TEDx Talks, “Is Algae the Ink of the Future?,” still located at 6:17, 10:03, August 22, 2016, https://livingink.co/news); (d) the three phases of the ink from algae obtention process. Images courtesy of Living Ink. Solaga: (e) function diagram of biofilm filtering air; (f) transferring biofilm onto hard surface (available at Solaga UG, “zibb,” Vimeo video, still located at 00:26 and 01:32, 3:14, October 17, 2019, https://vimeo.com/367026725); (g) biofilm in various dimensions. Images courtesy of Solaga.

Figure 12 Ecovative’s visualizations of the design potential of materials biofabricated from mycelium. (Left to right; top to bottom) MycoComposite™: round planter close up, material properties, MycoComposite block (foreground) (still taken from animated picture available at https://ecovativedesign.com/mycocomposite), Seed welcome kit, Mush Lume hemi pendant (Image courtesy of Grown.bio × Ecovative, design and photography by Danielle Trofe (2020, NY)), square planter, composted mycelium. MycoFlex × Mylo (ex-partnership): material properties, lightweight and breathability. MycoFlex: MycoFlex close up, material properties, rebound test (still taken from animated picture available at https://ecovativedesign.com/apparel), hydrophobic test, compression test (still taken from animated picture available at https://ecovativedesign.com/ourfoundry), squeezing (still taken from animated picture available at https://ecovativedesign.com/ourfoundry), hypoallergenic, safe, padding for backpack straps, glove liner, footwear, hygienic disposable products. Images courtesy of Ecovative.

Figure 13 Mycoworks' visualizations of the design potential of materials biofabricated from mycelium. (Left to right; top to bottom) Landing page of Reishi™'s story "Reishi™ launch at New York Fashion Week" (https://www.madewithreishi.com/stories/reishi-launch-at-new-york-fashion-week), Fine Mycelium sheet, Reishi detail, table of Reishi's Vartest results in "A Story of superior quality," Reishi detail in "A new class of fine materials," test of Reishi's performance in Reishi's story "A Story of superior quality," leather working tools image in Reishi's story "A new class of fine materials," Hand Stitching (available at Mycoworks, Vimeo video, still located at 00:01, 00:13, February 4, 2020), Edge Scoring (available at Mycoworks, Vimeo video, still located at 00:01, 00:02, February 4, 2020), Edge Skiving (available at Mycoworks, Vimeo video, still located at 00:01, 00:06, February 4, 2020), Gluing (available at Mycoworks, Vimeo video, still located at 00:01, 00:04, February 4, 2020) — (all the videos are available at https://www.madewithreishi.com/stories/fabricating-with-reishi), in preparation for hand-stitching a pricking iron is used to mark the desired thread spacing in Reishi's story "Through the eyes of master leather artisan Béatrice Amblard," Brown Natural (Regular and High Strength) and Black Emboss in Reishi's story "Our products," Cover of Reishi's story "A new class of fine materials," Erin Pollard, Summer Rayne Oakes and Elettra Rossellini Wiedemann attend a private dinner for Reishi at Il Buco in Reishi's story "Reishi™ launch at New York Fashion Week," Visitors to Mycoworks' Elizabeth Street showroom experience Reishi for the first time in Reishi's story "Reishi™ launch at New York Fashion Week," Curtidos Badia (since 1889) logo (available at Mycoworks, Vimeo video, still located at 00:07, 2:33, February 3, 2020, https://www.madewithreishi.com/stories/curtidos-badia-partnership). Images courtesy of Mycoworks and www.madewithreishi.com @mycoworks @madewithreishi.

Figure 14 Mogu's visualizations of the design potential of materials biofabricated from mycelium. (Left to right; top to bottom) acoustic mycelium panels: Mogu plain detail, acoustic performance, texture, and touch; Mogu panels: wave, fields, plain, kite, Mogu wave interiors, Mogu kite interiors; resilient mycelium floors: oyster irregular shapes, oyster texture, oyster square tiles, oyster interiors. Images courtesy of Mogu.

Figure 15 Spiber's visualizations of the design potential of materials biofabricated from bacteria. (Left to right; top to bottom) Brewed Protein structural protein powder developed by Spiber. The properties of Brewed Protein materials can be customized to match the needs of the end user; products developed in collaboration with sacai, featuring a Brewed Protein and cotton blend. Sacai tee black (front) and sacai tee grey (front). Source: sacai; joint development project with GOLDWIN Inc. and American longboard manufacturer Loaded Boards. As of September 2019, development is underway of a new material utilizing a bamboo (cellulose) core laminated with Brewed Protein textile; THE NORTH FACE ALTER store in Omotesando, prepared for a press announcement for T-shirt on June 20, 2019; product resulting from joint research and development with GOLDWIN Inc. The MOON PARKA is the world's first outerwear jacket to utilize structural protein materials. (MOON PARKA is a trademark of Spiber Inc. and GOLDWIN INC.); collaboration with world-renowned fashion designer Yuima Nakazato at Paris Fashion Week Haute Couture Fall/Winter 2019 (most of the material used in the collection comes from processed Brewed Protein materials) and Spring/Summer 2020 (each look featured in the collection utilized Brewed Protein materials). Images courtesy of Spiber Inc.

Figure 16 AMSilk's visualizations of the design potential of materials biofabricated from bacteria. (From left to right) Biosteel: wire, textile, Adidas Futurecraft Biofabric shoes, shoe fiber, shoe textile. Images courtesy of AMSilk.

Figure 17 Bolt Threads' visualizations of the design potential of materials biofabricated from bacteria. (Left to right) Microsilk™: spools of gold Microsilk, Gold MoMa dress close up, Gold MoMa dress lifestyle, Microsilk Tennis lifestyle, Microsilk Tennis dress. Images courtesy of Bolt Threads, photography by Ashley Batz.

Figure 18 Algix's visualizations of the design potential of materials biofabricated from algae. (Left to right; top to bottom) large BLOOM™ foam sheet; colored BLOOM foam sheets; compression-molded EVA insoles (Rise); estimated eco-facts based on a product weighing 200 grams; total liters of clean water + total liters of clean air (clean water + clean air certification); examples of brand allies partnering with BLOOM to clean water and air with every product (VivoBarefoot, Equilibrium, Tentree, Surftech); BLOOM infinite logo; nature-and water-inspired background landscapes. Images courtesy of Algix, LLC.

Figure 19 Living Ink's visualizations of the design potential of materials biofabricated from algae. (Left to right) sample of Algae Ink™ pigment (TEDx Talks, "Is Algae the Ink of the Future?," still located at 6:17); offset and packaging printing for various brands on several types of paper differentiated by thickness and color background. Images courtesy of Living Ink.

Figure 20 Solaga's visualizations of the design potential of materials biofabricated from algae. (Left to right; top to bottom) detail of algae biofilm; diagram highlighting biofilm's potential indoor and outdoor uses; detail of biofilm encasing with slot to allow the air to flow (Solaga UG, "zibb," still located at 01:57); laser-engraved biofilm; detail of algae biofilm cut with scissors (Solaga UG, "zibb," still located at 01:18); algae biofilm used in Alwe indoor and outdoor decor in different contexts. Images courtesy of Solaga.

Figure 21 Commonly used terms (N = 61 words) to define fungi- ($n_{fungi\ cluster}$ = 27 words), bacteria- ($n_{bacteria\ cluster}$ = 24 words), and algae-based materials ($n_{algae\ cluster}$ = 10 words), ordered alphabetically among material categories. Similar terms among two material categories indicated with *; similar terms across all three material categories indicated with **. © 2021 Patrizia D'Olivo and Elvin Karana.