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MATERIAL INNOVATION INITIATIVE

White Space Analysis 2021

The Next-gen Materials Industry

Nov 2021

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INTRODUCTION

The Material Innovation Initiative (MII) introduced and analysed the emerging next-gen material industry in our State of the Industry Report (June 2021). With that expertise, MII goes deeper in this report to identify the white space opportunities in next-gen materials for companies, scientists, and investors. The Mills Fabrica, an investor and ecosystem builder in sustainable food and fashion, brings its learnings and insights as an early mover in these white spaces.

In this report, we use the term white space to refer not only to areas without current competition, but also to new technology and gaps in existing markets.[1] We identify seven areas with significant opportunities for innovation in the next-gen material industry, broadly defined. Our goal is to direct interests, attention, and resources to innovate for the benefit of accelerating the entire next-gen materials industry.

In the bonus section, the Mills Fabrica applies their expertise in both spaces to highlight the parallels between alternative proteins and next-gen materials. Their insights show how the next-gen materials space is likely to develop and what we can learn from the alternative proteins industry.

Whether you are a material startup looking for high growth opportunities, a scientist developing a new technology or material, or an investor thinking of strategically diversifying into next-gen materials, we are certain this report will inspire your next move.

In order to come to grips with white space in this industry, we need to understand the following:

- We should not expect next-gen innovators to single-handedly solve the vast challenges of disrupting the global textiles, chemicals, and additives markets.
- Performance and aesthetics are absolute requirements for next-gen products, and meeting them may require sacrifices in certain areas of sustainability at this time.
- The research, development, and scale-up associated with novel, sustainable material feedstocks and chemistries that can be adopted by next-gen innovators take time and investment.
- There is no such thing as a “perfectly sustainable” material or product.

1 Mark W. Johnson, “Where Is Your White Space?” Harvard Business Review, Feb 12, 2010. https://hbr.org/2010/02/where-is-your-white-space

At the Material Innovation Initiative, we believe in making progress with the goal of perfection; perfection should not be the enemy of better. We trust that most innovators will rely on the best available options for sustainable formulation components, but completely phasing out less sustainable chemistries and additives is not always easy. MII will continue to identify and explain both opportunities and challenges so that the next-gen industry can iteratively move towards lower environmental impacts.

> "*Sustainability is always a series of compromises based on priorities and we need a lot of people doing some things better, rather than a few people doing everything perfectly.*"
>
> Dr. Amanda Parkes, Pangaia's chief innovation officer

In this white space mapping process, we seek to look at the material landscape up and down the value chain with a new lens. We want to identify unmet and unarticulated needs. These are not only missed opportunities, but also barriers to the growth and adaptation of next-gen materials. We need to direct interests, attention, and resources to fill these gaps for the benefit of accelerating the entire next-gen materials industry.

The next-gen materials industry will grow for the same reasons that alternative proteins have accelerated in the past few years. Conventional livestock-derived materials such as leather, fur, silk, wool, down, and exotic skins are widely used in the fashion, home goods, and automobile industries. It is a common misconception that animal-based materials are simply byproducts from industrial animal agriculture that primarily supplies to the food industry. And that misconception may have contributed to the next-gen materials industry being about five to ten years behind alternative proteins. Leather, for example, is the second most profitable product of a cow; and for fur, silk, and exotic skins, the animal material itself is the most profitable product.[2] Industrial animal farming is a leading cause of many of the pressing problems of our time, including climate change, biodiversity loss, environmental degradation, public health risks, and animal cruelty. Given that at least two thirds of a brand's environmental footprint can be attributed to its choice in raw materials,[3] if we hope to move rapidly toward a more sustainable materials industry, we need alternatives to animal materials.

2 USDA Market News, "USDA By-product drop value (steer) for Central U.S.," ams.usda.gov, May 25, 2021. https://www.ams.usda.gov/mnreports/nw_ls441.txt#:~:text=The%20average%20value%20of%20hide,down%200.58%20from%20last%20year

3 Global Fashion Agenda and The Boston Consulting Group, Pulse of the Fashion Industry 2018 (May 2018): 18. https://globalfashionagenda.com/pulse-of-the-fashion-industry-2018-report-released/

The co-founders of Material Innovation Initiative, Nicole Rawling and Stephanie Downs, both came from the world of alternative protein.

> *"STEPHANIE AND I HAVE SEEN THIS SORT OF INDUSTRY-WIDE CHANGE HAPPEN BEFORE, AND TODAY'S MATERIALS INDUSTRY LOOKS VERY FAMILIAR TO US."*
>
> NICOLE RAWLING, CO-FOUNDER AND CEO OF MATERIAL INNOVATION INSTITUTE

In 2019, McKinsey & Co. estimated the market base for alternative protein at approximately $2.2 billion compared with a global meat market of approximately $1.7 trillion. We estimate that the global wholesale market size for next-gen materials will be approximately $2.2 billion (USD) in 2026, representing a 3% share of an addressable market of over $70 billion.

DEFINITIONS

"**Next-gen materials**" are livestock-free direct replacements for conventional animal-based leather, silk, wool, down, fur, and exotic skins ("incumbent materials"). Next-gen materials use a variety of biomimicry approaches to replicate the aesthetics and performance of their animal-based counterparts.

"Current-gen materials" are those used to substitute for animal-derived materials by winning on price. Synthesized leather made from petrochemicals, for example, sells at wholesale at one-third the price of the animal leather equivalent. We generalise these petroleum-based alternatives (e.g., polyurethane (PU), polyvinyl chloride (PVC), acrylic fiber) as "current-gen materials," but their current applications in the market are far beyond animal-based material replacements. More clothing is made from polyester and nylon, both plastics, than from cotton. Examples of "current-gen" alternatives include PU for leather, polyester for silk, or acrylic for wool.

"Disruptive textile technology" refers to material innovations that do not directly replace animal-based materials, but that may become promising feedstocks or resources for next-gen material innovation. Sustainable innovation in synthetics such as bio-based, biodegradable, or recycled polyester or polyurethane, and in sustainable renewable-sourced fibers such as cellulosics and natural fibers, could have broad impacts in the plastics and textiles industries as a whole, as well as in the next-gen materials space. MII hosts a disruptive textile technology database to provide next-gen material innovators an easy way to find potential collaborators or suppliers.

"bio-based" refers to materials wholly or partly derived from biomass such as plants, trees or fungi (the biomass can have undergone physical, chemical or biological treatment).[4]

4 In this report, we modify the European Committee for Standardization's definition of "bio-based products" so as not to include any animal-derived products.
Institute for Sustainable Communities et al., Spinning Future Threads: The Potential of Agricultural Residues as Textile Fibre Feedstock (June 2021): 22.
https://laudes.h5mag.com/laudes/agri-waste_report_highlights/home/9656/agri_waste_report_2021_07_01.pdf

EXECUTIVE SUMMARY

Due to the nascency of the next-gen material industry, current white spaces are seated primarily in the early phases of material innovation: identifying target products and technical strategies to attain performance and sustainability. These white spaces deal with opportunities in underserved product applications (White Space 1), sustainable feedstock and additives (White Spaces 2,3,4), versatile end-of-life strategies (White Space 5), implementing bottom-up materials design in R&D (White Space 6), and hot spots in biotech process challenges (White Space 7). Below is a brief summary of the key findings from each white space:

1 SUBCATEGORIES WITH LIMITED INNOVATION

silk, down, fur, wool, and exotic skins

- Approximately 2/3 of current players in the next-gen materials industry target next-gen leather, leaving silk, wool, down, fur, and exotic skins with limited innovation efforts.
- Silk, fur, and exotic skin markets, in particular, are attractive for early stage innovators. High value product targets could enable a faster path to price parity than commodity markets.
- For example, polyester yarn hovers around $1/kg,[5] while raw silk averages around $55/kg.[6]
- These underserved product categories currently mean a lack of competition, which may be attractive to innovators and investors looking to enter the next-gen materials industry.

2 100% "SUSTAINABLE"?

bio-based resins, coatings, binders, dyes, finishes

- Innovations in components of next-gen materials, including coatings and dyes, could lead to more holistically sustainable formulations.
- Innovation in sustainable alternatives to fossil fuel-derived polyurethane would make a big impact in the next-gen leather industry. PU is often the choice for binders or coatings because of its versatility and performance attributes. We need bio-based PU formulations reliant on green chemistry, or entirely new resins to lower environmental impact.
- Across all next-gen material categories, additives, dyes, and finishes should also be considered by material innovators and converters, as these inputs also play an important role in product sustainability.

3 BEYOND POLYESTER

100% bio-based synthetic fibers

- Polyester is currently one of the most common and versatile formulation inputs for next-gen materials, finding use in nearly every product category.
- Innovation in sustainable synthetics is a target for the entire textile industry, but these efforts could apply to alternatives to animal-derived materials.
- Bio-based synthetic fibers can help reduce the reliance on petrochemical derivatives, and biodegradable fibers may enable alternative pathways at end-of-life.

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5 Fibre2Fashion.com, "Polyester Filament Yarn Market," accessed Sep 9, 2021. https://www.fibre2fashion.com/market-intelligence/textile-market-watch/polyester-filament-yarn-pfy-price-trends-industry-reports/5/?gcode=1

6 Bhavanishankar, "Good price for green cocoons - is it a boon or curse?" Fibre2Fashion.com, May 2013. https://www.fibre2fashion.com/industry-article/6905/good-price-for-green-cocoons-is-it-a-boon-or-curse-

4

NEW BIOFEEDSTOCK

biodiscovery and processing innovation for natural and cellulosic fibers and materials

- Natural and cellulosic fibers and materials are another versatile input for next-gen formulations.
- Novel biofeedstock, derived from agricultural waste or low impact natural resources are currently attractive opportunities for next-gen innovators.
- Billions of tonnes of unused agricultural waste products around the globe have potential for use in cellulosic or natural fibers.
- There is also a wealth of opportunity in process solutions to transform nature-based derivatives into scalable, high performance next-gen products.

5

LET'S GET VERSATILE

Multiple pathways at end of life

- Impending regulations and cost incentives will continue to push end-of-life waste strategies to the forefront. New textile materials entering the market are under pressure to fit into a closed-loop supply chain.
- While many of the circular end-of-life options show promise, they are also plagued with bottlenecks to implementation. We currently landfill or incinerate nearly 75% of our textiles.[7]
- Next-gen material innovators have an opportunity to design-in versatile end-of-life strategies into their products to meet these needs and reduce consumer burden.

6

MATERIALS SCIENCE DONE RIGHT

bottom-up material design

- The incumbent animal-derived materials rely on intricate interplay between composition, structure, and properties to achieve their performance.
- Innovators looking to replace these incumbents in the form of next-gen materials should start from the bottom-up: designing materials that closely mimic the hierarchical structure and composition of leather, silk, wool, down, fur, and exotic skins.
- Using iterative materials science principles and biomimicry, next-gen materials can more closely resemble and perform like the incumbents. end-of-life.

7

BIOTECHNOLOGY SCALE-UP

cellular agriculture at scale

- Next-gen innovators have begun to explore the opportunities of cellular agriculture to produce sustainable alternatives to animal-derived products.
- Using cultivated animal cells, mycelial growth, or building blocks derived from microbes, these approaches may transform materials manufacturing.
- However, these budding technologies rely on new-to-the-world science and underdeveloped manufacturing at-scale, with multiple pain points in need of resolution.
- Strain engineering, optimization of media/process conditions, and the conversion of raw outputs to finished products are each ripe for targeted innovation to mitigate risks during scale-up.
- Stakeholders in the next-gen industry should understand that biotech innovation requires investment and patience to be successful.

7 Ellen MacArthur Foundation et al., A New Textiles Economy: Redesigning Fashion's Future (2017): 20. https://emf.thirdlight.com/link/kccf8o3ldtmd-y7i1fx/@/preview/1?o

1. SUBCATEGORIES WITH LIMITED INNOVATION

silk, wool, down, fur, and exotic skins

As demonstrated in MII's State of the Industry Report: Next-Gen Materials, the last 5 years have seen an increase in the number of innovators and investments in next-gen materials. However, of the ~75 material innovators referenced in our report, nearly 50 of them are innovating in next-gen leather (Figure 1). That means the remaining third of innovations are split across five subcategories: silk, wool, down, fur, and exotic skins. It is clear that these relatively neglected categories are white spaces in and of themselves.

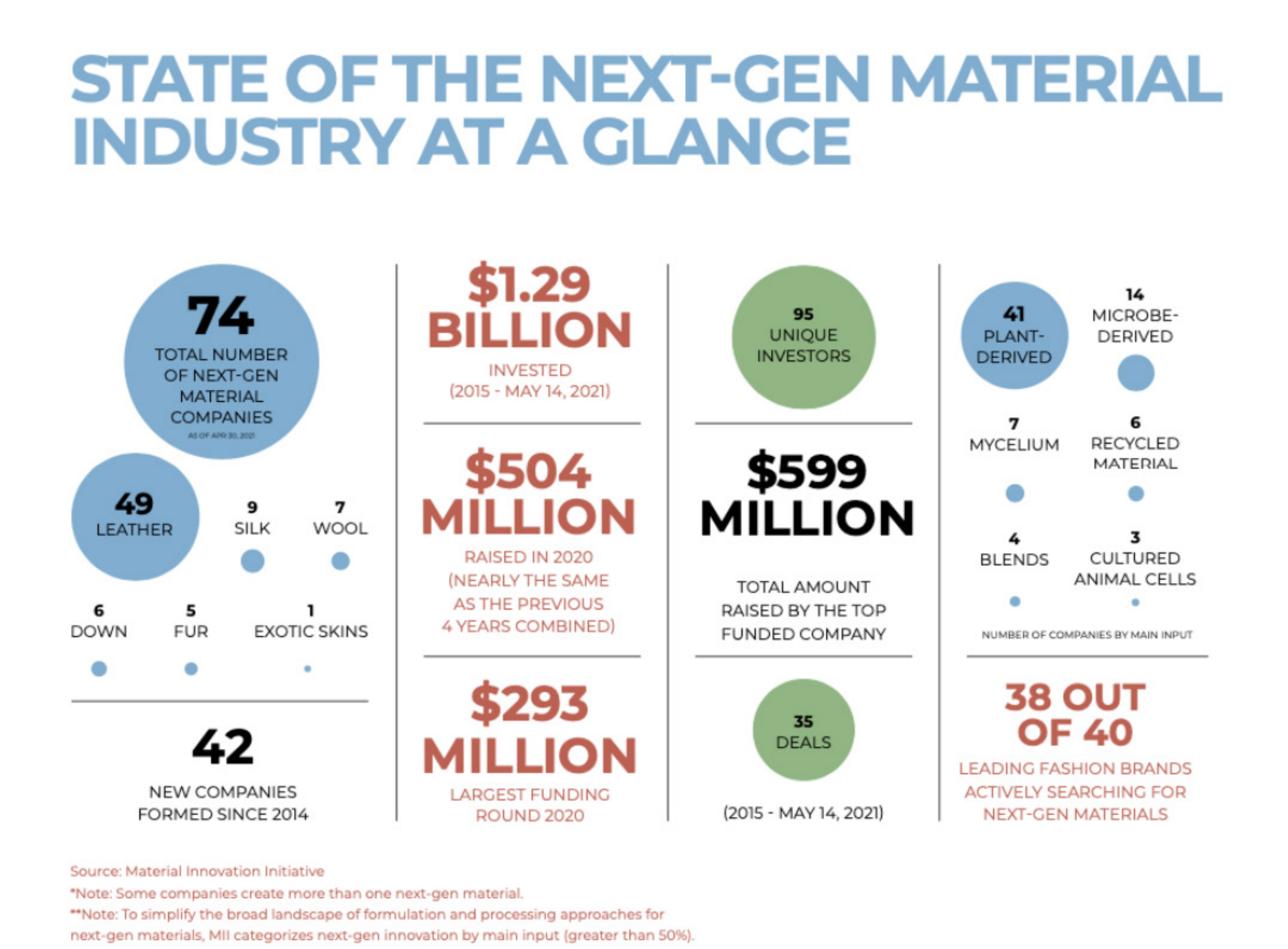

Figure 1. State of the Next-Gen Material Industry (June 2021). Available at: https://www.materialinnovation.org/reports

While it may not be time to call the next-gen leather sector "crowded", the flurry of activity in this single sector does not go unnoticed. The concentration of innovators in next-gen leather is driven by consumer demand and market potential. Consumers are demanding animal-free, sustainable, high performance alternatives, but the current marketplace is unable to supply this demand. All but 2 of the 40 top brands MII has worked with are actively looking for next-gen leather solutions to fill this gap.

Moreover, of the next-gen material categories, incumbent animal-derived leather production encompasses the largest volume. The hides and skins of over 1.4 billion animals were used to make leather in 2020 alone, for a total of ~12.5 million tonnes of leather.[8] Leather prices vary from ~$2-15/square foot.[9] No single innovation will be able to disrupt this large market. We need many innovators producing a wide variety of next-gen leather products to supply the fashion, homegoods, automotive, and related industries.

Although the other next-gen material categories have lower annual volumes of production, these markets are still prime for disruption. Annual sheep's wool production was over 1 million tonnes in 2020, with down and feathers at over 0.5 million tonnes.[10] Fine wool from Australia is currently priced at ~$10/kg,[11] with down-feather mixes approaching up to $80/kg in some circumstances.[12]

Silk production takes a smaller share at 0.11 million tonnes produced,[13] but this statistic undersells the value of silk. Silk is one of the most expensive textile fibers on the market, with raw silk yarn averaging about $55/kg,[14] and approaching $100/kg for high quality grades. A single yard of silk fabric can cost $100.[15] As of 2000, the annual income of one silk tradehouse, the China National Silk Import and Export Corporation, was $2-2.5 billion.[16]

The global exotic skin and fur markets are difficult to estimate, due to the diversity of animal species as well as the countries involved in their production. For perspective, over 45 million fur pelts of various species produced in Europe in 2015 alone were auctioned at over €2 billion.[17] Finished exotic skins such as crocodile can exceed $1000 per skin,[18] and desirable furs such as bobcats can reach ~$200 per pelt.[19]

Thus despite the lower production volume of incumbent silk, wool, down, fur, and exotic skins compared to leather, next-gen innovators can capitalize on the great value in these material subcategories.

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8 Textile Exchange, Preferred Fiber & Materials Market Report (2021): 55. https://textileexchange.org/wp-content/uploads/2021/08/Textile-Exchange_Preferred-Fiber-and-Materials-Market-Report_2021.pdf

9 BuyLeatherOnline.com, "Leather by the yard and by meter: prices and where to buy," Sep 30, 2019. https://buyleatheronline.com/en/blog/leather-by-the-yard-n84

10 Textile Exchange, Preferred Fiber & Materials Market Report (2021): 5. https://textileexchange.org/wp-content/uploads/2021/08/Textile-Exchange_Preferred-Fiber-and-Materials-Market-Report_2021.pdf

11 YCharts.com, Australia Fine Wool Spot Price: 9.095 USD/kg for Jul 2021, accessed Sep 9, 2021. https://ycharts.com/indicators/australia_fine_wool_spot_price

12 Young-Ju Kim, "Duck down prices quack under pressure," KoreaJoongAngDaily.joins.com, Jun 8, 2018. https://koreajoongangdaily.joins.com/2018/06/08/industry/Duck-down-prices-quack-under-pressure/3049130.html

13 Textile Exchange, Preferred Fiber & Materials Market Report (2021): 53. https://textileexchange.org/wp-content/uploads/2021/08/Textile-Exchange_Preferred-Fiber-and-Materials-Market-Report_2021.pdf

14 Bhavanishankar, "Good price for green cocoons - is it a boon or curse?" Fibre2Fashion.com, May 2013. https://www.fibre2fashion.com/industry-article/6905/good-price-for-green-cocoons-is-it-a-boon-or-curse-

15 Emma Fierberg, "Why silk is so expensive," BusinessInsider.com, Oct 1, 2018. https://www.businessinsider.com/why-silk-is-so-expensive-dress-sheets-robe-fabric-2018-9

16 International Trade Forum Magazine, "Silk in World Markets," TradeForum.org, Jan 1999. https://www.tradeforum.org/Silk-in-World-Markets/#:~:text=Silk%20has%20a%20miniscule%20percentage,market%2Dless%20than%200.2%25

17 Fur Europe, Fur Europe Annual Report (2015): 52. http://fureurope.eu/wp-content/uploads/2015/02/FE-Annual-Report-2015-Single-Pages.pdf

18 Rojé Exotic Leather, "Buy Exotic Skins Online," accessed Sep 9, 2021. https://store.rojeleather.com/

19 Serge Lariviére, "Fur Market Report Summer 2021: Muskrat Prices, the First Sign of Market Recovery?" TrapperMag.com, Jun 4, 2021. https://www.trappermag.com/article-index/muskrat-prices-the-first-sign-of-market-recovery

This is important to note, in particular due to the current search for plastic alternatives, leading to many innovations which target themselves as a replacement for fossil-fuel based polyester. However, polyester yarn hovers around $1/kg,[20] and the annual production of polyester is over 57 million tons (or over half of the global textiles production annually).[21]

For material innovators who find themselves battling with achieving scale and price parity, why not target animal-derived materials that have higher unit costs and lower incumbent production volumes? For example, an innovator in next-gen silk needs only make ~10,000 kg of silk to replace 10% of the current commercial animal-derived silk. Even early pilot production can make a big impact in the search for animal-free silk, and incumbent silk's high costs make for more attainable profits. Compare this with an attempt to disrupt the fossil-based polyester industry, with its far more daunting low price points and high volume (Figure 2).

The synthetic market is not out of reach for an innovator targeting silk or other animal-derived materials, however. Recall that animal-derived materials were the original performance fibers.[22] Rayon and nylon were historic replacements for silk, with current standby polyester capturing the current synthetic silk market. Silk, wool, and other animal-derived materials were overtaken by synthetics because of lower costs, versatility, launderability, and ease of manufacturing. Next-gen materials can recapture the lost market share of incumbents, if they can replicate the positive attributes of natural materials (e.g., strength, thermal regulation, aesthetics), while improving upon the negatives (e.g., sustainability, animal welfare, high costs). Innovation in the next-gen materials space has a greater long term potential beyond that of the current incumbent markets: the current-gen synthetic market.

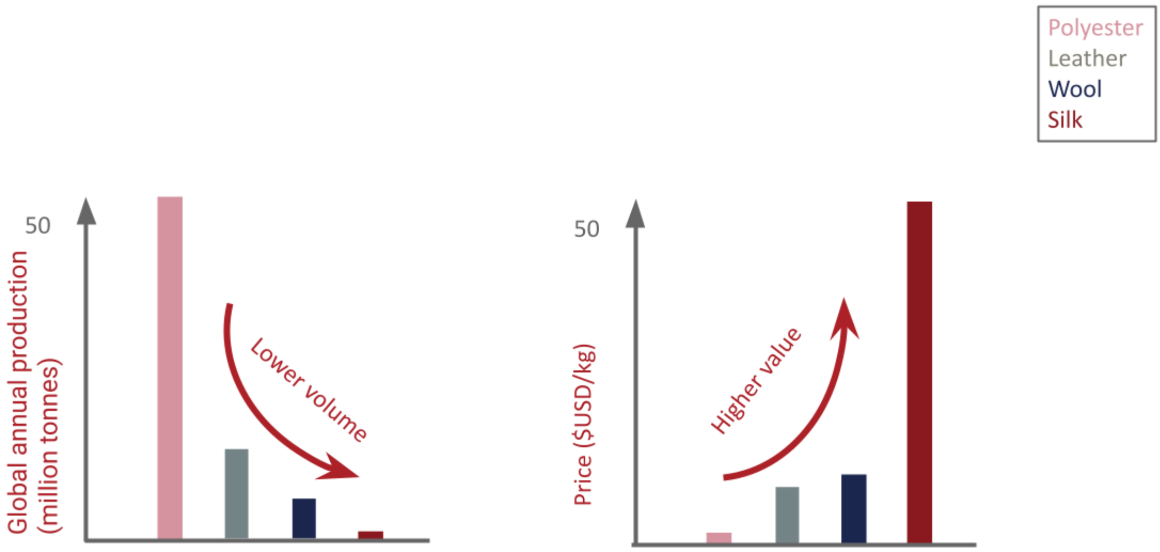


Figure 2. Higher value, low volume materials such as silk could be an attractive target for next-gen innovators.
Note: Chart is for illustrative purposes only.

20 Fibre2Fashion.com, "Polyester Filament Yarn Market," accessed Sep 9, 2021. https://www.fibre2fashion.com/market-intelligence/textile-market-watch/polyester-filament-yarn-pfy-price-trends-industry-reports/5/?gcode=1

21 Textile Exchange, Preferred Fiber & Materials Market Report (2021): 73. https://textileexchange.org/wp-content/uploads/2021/08/Textile-Exchange_Preferred-Fiber-and-Materials-Market-Report_2021.pdf

22 Bella Webb, "Sustainable performance wear: Possibility or pipe dream?" VogueBusiness.com, Aug 26, 2021. https://www.voguebusiness.com/sustainability/sustainable-performance-wear-possibility-or-pipe-dream?uID=895fc2d3a1a2689eb26202ffcc8f5f285696f29dfba9c7831581940ad09d2cf8

Investors and innovators should also consider the relative lack of competition in these untapped areas. There is still room for more next-gen leather innovators, of course, but the landscapes are much more sparse in the other categories. A few emerging innovators are actively pursuing these white spaces. One next-gen fur innovator, House of Fluff, currently creates faux fur materials based on recycled and/or bio-based feedstock, with goals to go completely petroleum free in the near future (See White Space 3.) Spiber is a promising innovator, using fermentation processes to produce protein-based fibers derived from spider silk genes, which may have applications across silk, cashmere, and wool.

Further innovation in the relatively unexplored next-gen categories of silk, wool, down, fur, and exotic skins has the potential to impact the market and meet consumer demand.

A recent survey by MII and North Mountain Consulting Group found that 94% of respondents in the United States were open to purchasing next-gen materials.[23]

Nearly half of these respondents were highly likely to purchase, and 39% would actually pay more for sustainable, animal-free versions of leather, wool, down, silk, fur, and exotic skins.

FOLLOW-UP READING AND RESOURCES RELATED TO THIS TOPIC:

Material Innovation Initiative. State of the Industry Report 2021: Next-Gen Materials and Consumer Research Reports.
Available at: https://www.materialinnovation.org/reports

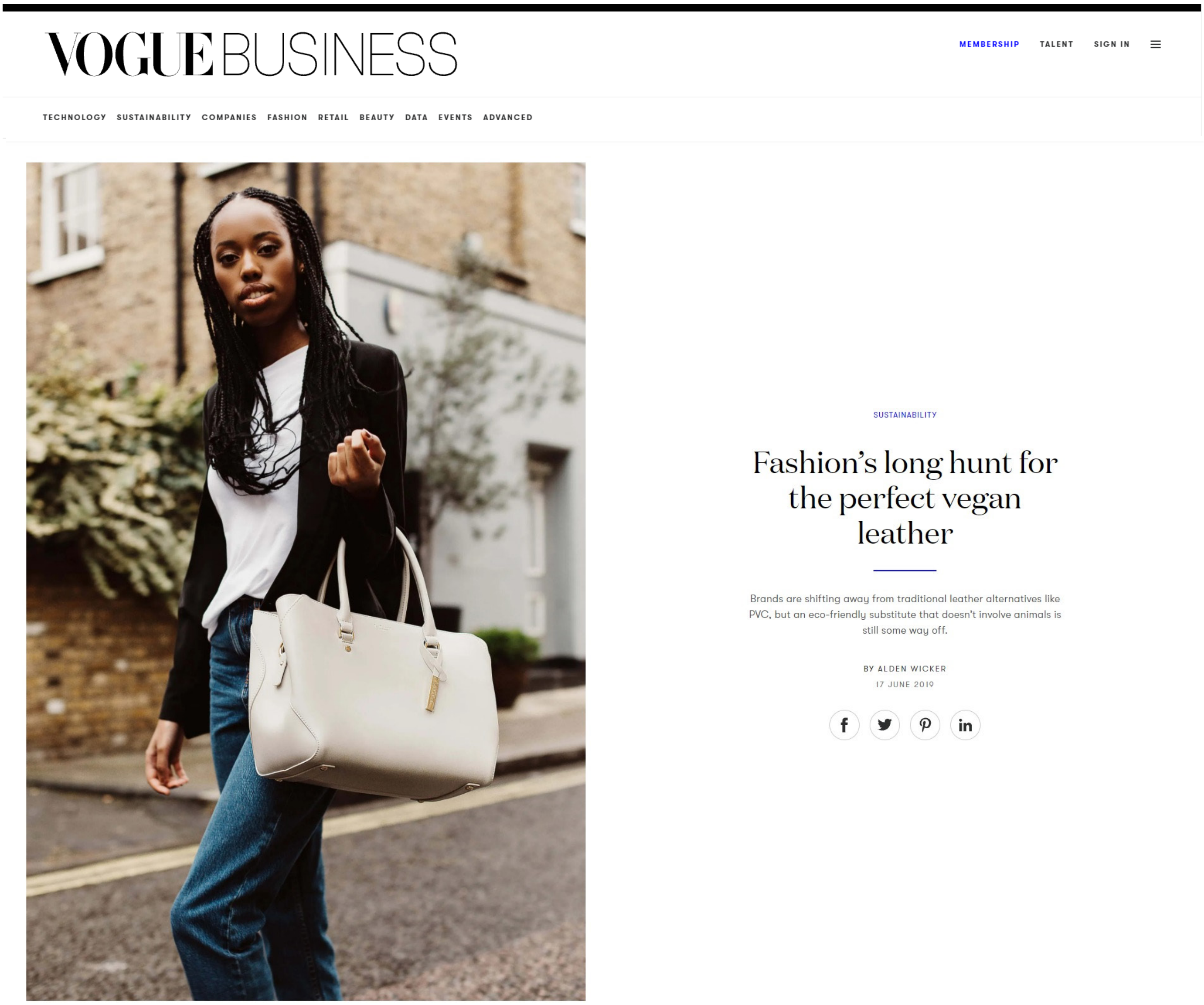
Textile Exchange. Preferred Fiber and Materials Market Report 2021.
Available at: https://textileexchange.org/wp-content/uploads/2021/08/Textile-Exchange_Preferred-Fiber-and-Materials-Market-Report_2021.pdf

23 Keri Szejda and Tessa Urbanovich, Consumer Adoption of Next-Gen Materials: A U.S. Segmentation Study, Conducted by North Mountain Consulting Group for Material Innovation Initiative (Sep 2021): 1-31. https://www.materialinnovation.org/consumer-research-1

2. 100% "SUSTAINABLE"?

bio-based resins, coatings, binders, dyes, finishes

Although the next-gen ecosystem has made great strides to incorporate lower impact feedstock such as agricultural waste and microbial products, a gap remains in ensuring that the entire textile formulation incorporates sustainable inputs. Many formulations still require petroleum-based derivatives and hazardous additives to achieve functional performance criteria, and thus have limited end-of-life options. The next-gen material industry needs continued development and commercialization of sustainable alternatives to binders, coatings, dyes, additives, and finishing agents, in order to achieve holistically sustainable fabrics.



Source: https://www.voguebusiness.com/technology/vegan-faux-leather-stella-mccartney-prada-versace

PVC and other vinyl-based polymers are some of the oldest resins used to make synthetic leather in the form of coated fabrics, which gained popularity in the mid-20th century due their desirable properties such as waterproofness, durability, and flame-retardance.[24]

However, PVC is generally considered one of the most damaging plastics that exist.[25]

Its manufacturing process relies on fossil fuel inputs, can release hazardous chlorine compounds and dioxins, and uses hazardous phthalate plasticizers to induce flexibility. (Phthalates make up 3 out of 10 of the most noticed chemicals by California's hazardous chemical labeling laws.)[26] PVC also has a low recycling rate and can contribute to micro- and macroplastic pollution. As such, most recent innovations in synthetic leather have avoided PVC and instead use PU.

PU is a versatile and high performing synthetic polymer. Intrinsically water-resistant and tough, with the ability to be foamed, cast as a dispersion, spun as a fiber, or molded into complex shapes, PU has found broad applications across packaging, medical applications, electronics and appliances, automotive, the built environment, and of course, textiles.[27] In the textiles space, PU finds the most use in synthetic leather, waterproof outerwear, and "stretch" fibers, often referred to as Spandex or Elastane.[28] In fact, animal-derived leather also uses PU as a coating in some instances.[29]

24 Chieftain Fabrics, "The history of vinyl fabric," ChieftainFabrics.com, accessed Sep 9, 2021. https://chieftainfabrics.com/the-history-of-vinyl-fabric/

25 Greenpeace, "PVC: The Poison Plastic," Greenpeace.org, Aug 18, 2003. https://www.greenpeace.org/usa/wp-content/uploads/legacy/Global/usa/report/2009/4/pvc-the-poison-plastic.html

26 Cal Biz Lit, "Proposition 65: The Most Commonly Noticed Chemicals in 2018," CalBizLit.com, Jan 14, 2019. https://www.calbizlit.com/cal_biz_lit/2019/01/proposition-65-the-most-commonly-noticed-chemicals-in-2018.html#:~:text=When%20we%20analyzed%20the%202016,Coal%20tar%2C%20DBP%20and%20BPA.

27 American Chemistry Council, "Chemistry in America: Polyurethane," AmericanChemistry.com, accessed Sep 9, 2021. https://polyurethane.americanchemistry.com/Applications/

28 American Chemistry Council, "Textiles," AmericanChemistry.com, accessed Sep 9, 2021. https://polyurethane.americanchemistry.com/Applications/https://www.americanchemistry.com/industry-groups/aliphatic-diisocyanates-adi/applications/textiles
Polymer Properties Database, "Polyurethane Fibers (Spandex), " PolymerDatabase.com, accessed Sep 9, 2021. https://polymerdatabase.com/Fibers/Urethane.html

29 Saiqi Tian, "Recent Advances in Functional Polyurethane and Its Application in Leather Manufacture: A Review," Polymers (Basel) 12, 9 (1996), published online Sep 2, 2020. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7565108/;
Best Leather, "What is Bovine Leather?" BestLeather.org, accessed Sep 9, 2021. https://bestleather.org/types-of-leather/bovine/

One of the reasons for the broad applications of PU is its adaptable chemistry. PU is typically based on the reaction of a polyol (or an alcohol with multiple -OH groups per molecule) and an isocyanate (R-N=C=O). Based on the type of polyol and type of isocyanate chosen for the reaction, and the ratio of these and other reactants (e.g., chain extenders), a wide range of functional properties can be realized.

However, like many petroleum-derived synthetics, this high performance comes at a detriment to sustainability. Isocyanates are associated with widespread occupational exposure threats,[30] thus making the manufacturing of traditional PU hazardous to workers if industrial hygiene controls are not properly implemented. Harsh solvents such as dimethylformamide (DMF) are often used to solution-coat PU onto fabrics and are also associated with hazard concerns.[31] Traditional PU is derived from non-renewable petroleum (and is thus associated with the damaging environmental impacts of fossil fuel extraction), and is difficult to recycle. Some research has indicated that some forms of PU can biodegrade in certain conditions, but more research is needed to fully understand the biodegradability of PU of varying formulations/structures, in different environments and timescales, and the effects of degradation byproducts.[32]

Importantly, bio-based innovation for PU has recently come to commercial scale. The polyol component of the formulation can be derived from biological sources such as plant oils or microbial fermentation products. However, the isocyanate component is still typically derived from fossil fuels. This limits typical PU formulations to only partial bio-based content. Certain advancements in non-petroleum derived isocyanates have been made by suppliers such as Covestro, and these have enabled 100% bio-based formulations of PU,[33] but scale, cost, and availability are still issues to address. Substantial research efforts to develop isocyanate-free formulations of PU[34] may enable 100% bio-based content, but these advancements remain largely academic at this time.

An improvement in process sustainability, in the form of waterborne or solvent-free PU dispersions, eliminates the need for hazardous solvents such as DMF that are used in traditional PU formulations. However, most of these solutions still suffer from end-of-life challenges in that recycling is difficult, and biodegradability is lacking.

30 Occupational Safety and Health Administration, “Safety and Health Topics: Isocyanates,” OSHA.gov, accessed Sep 9, 2021. https://www.osha.gov/isocyanates#:~:text=Health%20effects%20of%20isocyanate%20exposure,chest%20tightness%2C%20and%20difficult%20breathing.&text=The%20main%20effects%20of%20hazardous,nose%2C%20throat%2C%20and%20skin

31 Isaac Ramphal et al., “Greener Alternatives to Dimethylformamide Use in Polyurethane Synthetic Leather,” Greener Solutions: A Safer Design Partnership with Nike, Inc. (Fall 2019): 22. https://bcgctest.files.wordpress.com/2020/01/dmfchallenge_5486653_76369033_nike_finalreport-1.pdf

32 Gary T. Howard, “Biodegradation of polyurethane: a review,” International Biodeterioration & Biodegradation 49, 4 (2002): 245-252. https://www.sciencedirect.com/science/article/abs/pii/S0964830502000513

33 Doris de Guzman, “100% bio-based Polyurethane in the market,” GreenChemicalsBlog.com, Apr 27, 2015. https://greenchemicalsblog.com/2015/04/27/100-bio-based-polyurethane-in-the-market/

34 Mukesh S. Kathalewar et al., “Non-isocyanate polyurethanes: from chemistry to applications,” RSC Advances 3 (2013): 4110-4129. https://pubs.rsc.org/en/content/articlelanding/2013/RA/c2ra21938g

Checkerspot is one example of innovators developing sustainable PU feedstocks for a variety of applications. Checkerspot uses a platform of microalgae fermentation to produce precursors for polyurethane resins, foams, and textile finishing agents.

Innovators continue to target sustainable PU formulations due to their versatility and proven performance, but there is also a need for sustainable alternative binders and coatings in this space. Natural rubber derivatives, silicones, bio-based acrylates, nitrocellulose, and waxes are other options that may provide low impact solutions for waterproofing and/or mechanical performance. Advancements in biodiscovery and polymer chemistry may enable new raw material sources and engineered resins to fill this need, such as plant protein coatings by innovator Xampla. Tandem Repeat Technologies is also developing a material called Squitex, a fermentation-derived biodegradable protein inspired by squid proteins that may behave similar to spandex and PU.

In the next-gen materials space, Natural Fiber Welding has developed a platform for next-gen leather production that is certified 100% bio-based, using plant-derived resins, fibers, and fillers. Biophilica is currently developing a PU- and PVC-free next-gen leather based on green waste plant matter. There is a great need for continued innovation in bio-based, and circular and/or biodegradable (see White Space 5) resins to serve as flexible, durable binders and coatings for the next-gen leather industry.

Brands have highlighted the need for more sustainable options to traditional PU for applications such as synthetic leather. H&M group has pledged to make all PU used in their products "sustainable, for example bio based" by 2030, and as of 2020 has moved toward DMF-free, waterborne and/or solvent-free PU formulations.[35] Sustainably-minded brand Reformation has partnered with MII to continually strive for more sustainable synthetic leathers, currently employing bio-based PU:

> *"Clearly leather can really suck, but so can its alternatives... That's why we're using a leather alternative that's USDA biopreferred, which means it's made mostly of natural stuff like cereals and grains. It uses the lowest amount of virgin plastic we could find, but it's not perfect, so we're teaming up with the Material Innovation Initiative to push plastic-free leather alternatives forward."*

Reformation[36]

35 H&M Group, Case Study - Leading the change towards better PU: Phase out of DMFa based PU material by 2020 (Oct 2020): 1-4. https://hmgroup.com/wp-content/uploads/2020/10/Case-Study_DMFa-phase-out.pdf

36 Reformation, "Shoes Suck," TheReformation.com, accessed Sep 30, 2021. https://www.thereformation.com/pages/shoes-suck

Investors have identified this unmet need as an investment opportunity. Mission-backed VC firm Safer Made has made strides to identify green chemistry solutions for consumer products, and has also identified sustainable PU formulations as a white space opportunity.

> *"Function and performance catalyze the adoption of new materials. The most interesting alternatives will surpass the performance of incumbent isocyanate polyurethane in one or two applications by exploring new chemical space rather than focusing too narrowly on the current resin chemistry."*
>
> Marty Mulvihill, General Partner, Safer Made

Dyes, additives, and finishes

Another aspect of next-gen material formulations that requires attention is sustainable dyes and finishes. The additives and treatments that provide performance features such as color, luster, brightness, moisture management, flame retardancy, softness, stiffness, antimicrobial activity, and wrinkle-resistance are often overlooked when designing sustainable textiles. These additives and their application processes may result in toxic, bioaccumulative, and/or persistent chemicals in effluents resulting in environmental and ecological impacts. Effluents from the textile industry contribute to an estimated 20% of all freshwater pollution worldwide.[37] Dyes, additives, and finishes may also raise issues with worker safety.

A notable example is the use of per- or polyfluoroalkyl substances (PFAS) to impart stain and water resistance to textiles. These chemicals, similar to the composition of Teflon, are high performing additives that have recently come under scrutiny as "forever chemicals" associated with environmental and human health effects.[38] Other examples of widespread textile additives of emerging concern include brominated flame retardants[39] and many synthetic dyes used to color textiles.[40]

Such additives can also have an impact on the end-of-life for a next-gen textile. For example, the rate of biodegradation can change if fibers (more on biodegradation in White Space 5), are coated in synthetic treatments (e.g., durable water repellent coatings, or DWR[41]).[42] Dyes and fiber blends can also affect the recycling pathways for textiles. The variety of colors and fabric types add to the many hurdles associated with textile recycling realization.[43]

Innovators such as Huue, Colorifix, and Living Ink are developing bio-based inks derived from microbes, plants, and algae, and these may reduce our reliance on hazardous synthetic dyes. A powerhouse in the next-gen materials space, Pangaia, takes a platform approach to their material innovation. They develop and incorporate sustainable solutions across their formulation needs, including fibers, dyes, finishes, and more.

As next-gen innovators keep circularity and sustainability in mind, the role of additives in formulations needs to be part of the picture.

37 Forida Parvin et al., "A Study on the Solutions of Environment Pollutions and Worker's Health Problems Caused by Textile Manufacturing Operations," Biomedical Journal of Scientific & Technical Research 28, 4 (2020): 21832. https://biomedres.us/pdfs/BJSTR.MS.ID.004692.pdf

38 John Xiong and Elie Haddad, "Textile manufacturing and PFAS: three phases of risk," HaleyAldrich.com, Mar 16, 2021. https://www.haleyaldrich.com/resources/blog/textile-manufacturing-and-pfas-three-phases-of-risk/; Environmental Working Group, "What are PFAS Chemicals?" EWG.org, accessed Sep 9, 2021. https://www.ewg.org/pfaschemicals/what-are-forever-chemicals.html

39 Elizabeth Grossman, "Are Flame Retardants Safe? Growing Evidence Says 'No'," e360.yale.edu, Sep 29, 2011. https://e360.yale.edu/features/pbdes_are_flame_retardants_safe_growing_evidence_says_no

40 Rita Kant, "Textile dyeing industry an environmental hazard," Natural Science 4, 1 (2012): 22-26. https://file.scirp.org/Html/4-8301582_17027.htm

41 Patagonia, Inc., The Footprint Chronicles: PFOS, PFOA, and other Fluorochemicals (2013): 1-2. https://www.patagonia.com/on/demandware.static/Sites-patagonia-us-Site/Library-Sites-PatagoniaShared/en_US/PDF-US/pfoa_and_flourochemicals.pdf\

42 Marielis C. Zambrano et al., "Impact of dyes and finishes on the aquatic biodegradability of cotton textile fibers and microfibers released on laundering clothes: Correlations between enzyme adsorption and activity and biodegradation rates," Marine Pollution Bulletin 165 (2021). Published online Feb 6, 2021. https://www.sciencedirect.com/science/article/abs/pii/S0025326X21000643?via%3Dihub

43 Abigail Beall, "Why clothes are so hard to recycle," BBC.com/future, Jul 12, 2020. https://www.bbc.com/future/article/20200710-why-clothes-are-so-hard-to-recycle

FOLLOW-UP READING AND RESOURCES RELATED TO THIS TOPIC:

Material Innovation Initiative. Disruptive Textile Innovation Resources.
Available at: https://www.materialinnovation.org/disruptive-textile-innovation-resources

The ZDHC Foundation's Road Map to Zero and related resources.
Available at: https://www.roadmaptozero.com/

Safer Made and Fashion for Good. Safer Chemistry Innovation in the Textile and Apparel Industry.
Available at: https://www.safermade.net/textile-report

3. BEYOND POLYESTER

100% bio-based synthetic fibers

The ubiquity of polyester

Polyester accounts for more than 55% of all textile raw materials produced annually, with over 57 million tons produced in 2020 alone.[44] Polyester is public enemy number one in the fashion industry's search for more sustainable materials and in the larger anti-plastic crusade of recent years.[45] Therefore, sustainable alternatives to virgin, petroleum-derived polyester would certainly make a huge impact in the textile industry, including next-gen materials. But wait, didn't we just advise you in White Space 1 not to focus on the polyester market? Let us explain.

Polyester is often used as a replacement for silk, particularly in fast fashion applications. Polyester fleece is a common fabric in warm, fuzzy garments similar to wool or shearling. Some faux furs also employ virgin or recycled polyester fibers. Nonwoven polyester fill is a common alternative to down insulation in apparel and bedding.

Polyester fabrics are sometimes coated in PU to make synthetic leather, and microfiber polyester is often used as a synthetic suede or nubuck. In all these ways, polyester is a common "current-gen" alternative to animal-derived incumbents and finds its way into nearly every sub-category.

Therefore, next-gen innovators could consider sustainable improvements on these current-gen strategies, by developing and incorporating bio-based polyester fibers. Instead of targeting polyester for polyester's sake, target next-gen silk, wool, and/or leather instead, and consider sustainable alternatives to polyester as a means to this end.

Like many other synthetics such as PU, performance and versatility have led to the widespread use of polyester in textiles. As a thermoplastic resin, polyester can be molded into shapes, extruded into fibers, and applied as a coating. It finds applications as reinforcement for automotive tires, nonwoven personal hygiene products, beverage bottles, food packaging, and of course, textiles for fashion and homegoods.[46] Polyester's notable ability to be spun into fibers of varying diameter, cross-sectional shapes, and lengths, allows it to produce everything from soft, velvet-like microfiber, smooth, shiny satin fabrics, and rugged outerwear. Additives incorporated into the resin formulation can also tune the color, luster, and environmental performance of polyester fibers and fabrics.

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44 Textile Exchange, Preferred Fiber & Materials Market Report (2021): 73. https://textileexchange.org/wp-content/uploads/2021/08/Textile-Exchange_Preferred-Fiber-and-Materials-Market-Report_2021.pdf

45 Changing Markets Foundation, Fossil Fashion and Synthetics Anonymous Reports. Available at: https://changingmarkets.org/portfolio/fossil-fashion/

46 BYJU'S Classes, Chemistry: Synthetic Fibres and Plastics: Uses of Polyester, byjus.com, accessed Sep 9, 2021. https://byjus.com/chemistry/uses-of-polyester/

Polyester actually refers to a class of polymers containing an ester bond, and thus encompasses a wide variety of materials. The most common form of polyester, and that most used in textiles, is polyethylene terephthalate (PET). This form of polyester has a good balance of properties including heat stability, strength, flexibility, elongation, and moisture wicking capabilities.[47] In addition, polyester is one of the most affordable yarns and fabrics available today. Polyester yarn costs around $1/kg[48]; raw silk averages $55/kg.[49]

However, polyester shares many of the same drawbacks as PU - namely, environmental concerns. Polyester is derived from fossil fuels and has an energy-intensive manufacturing process. Per tonne of fiber, polyester spinning uses nearly 10x more energy compared to the cultivation and spinning of organic cotton.[50] Even though polyester is the most commonly recycled plastic and using recycled polyester can reduce the amount of energy required to make fibers,[51] polyester textiles are still associated with abysmal recycling rates: **less than 1% of clothes, of all material mixes, are recycled**.[52] This means that recycled polyester fabrics are typically made not from recycled textiles, but from recycled bottles. In addition, the traditional mechanical recycling process leads to a reduction in the quality of the polyester resin. Considering the demand for recycled polyester by the packaging industry, the fashion industry, and many more markets, there will not be enough high-quality recycled feedstock to serve all industries if recycling rates and processes do not improve.[53] Whether from recycled or virgin feedstock, however, polyester fibers are of growing concern for the release of microfibers into the environment. These microfibers are associated with widespread effects on ecosystems and human health.[54]

47 Sewport Support Team, "What is Polyester Fabric: Properties, How it's Made and Where," sewport.com, accessed Sep 9, 2021. https://sewport.com/fabrics-directory/polyester-fabric

48 Fibre2Fashion.com, "Polyester Filament Yarn Market," accessed Sep 9, 2021. https://www.fibre2fashion.com/market-intelligence/textile-market-watch/polyester-filament-yarn-pfy-price-trends-industry-reports/5/?gcode=1

49 Bhavanishankar, "Good price for green cocoons - is it a boon or curse?" Fibre2Fashion.com, May 2013. https://www.fibre2fashion.com/industry-article/6905/good-price-for-green-cocoons-is-it-a-boon-or-curse-

50 Marjorie van Elven, "How sustainable is recycled polyester?" FashionUnited.com, Nov 15, 2018. https://fashionunited.com/news/fashion/how-sustainable-is-recycled-polyester/2018111524577

51 Marjorie van Elven, "How sustainable is recycled polyester?" FashionUnited.com, Nov 15, 2018. https://fashionunited.com/news/fashion/how-sustainable-is-recycled-polyester/2018111524577

52 Changing Markets Foundation, Fossil Fashion: The hidden reliance of fast fashion on fossil fuels (Feb 2021): 1-24. http://changingmarkets.org/wp-content/uploads/2021/01/FOSSIL-FASHION_Web-compressed.pdf

53 Elizabeth Segran, "Recycled plastic isn't going to save us," FastCompany.com, Nov 12, 2019. https://www.fastcompany.com/90429087/recycled-plastic-isnt-going-to-save-us;
Changing Markets Foundation, Fossil Fashion: The hidden reliance of fast fashion on fossil fuels (Feb 2021): 1-24. http://changingmarkets.org/wp-content/uploads/2021/01/FOSSIL-FASHION_Web-compressed.pdf

54 Multiple Authors, "Special section: Our Plastics Dilemma," Science Magazine 373, 6550: 34-69, ScienceMagazineDigital.org, Jul 2, 2021. https://www.sciencemagazinedigital.org/sciencemagazine/02_july_2021/MobilePagedReplica.action?u1=41674394&pm=2&folio=35#pg35

Bio-based synthetic solutions

How can we solve these issues with polyester's sustainability while reaping the benefits of its versatility? Like the case for PU, finding bio-based solutions to polyester would reduce the reliance on fossil fuels and could lower environmental footprints. One of the most notable commercial-scale solutions on this front is Dupont's Sorona polyester, which uses fermentation products to create a 37% bio-based polymer comparable to PET or nylon, with 63% fewer emissions than nylon 6.[55] Sorona has been employed by current next-gen fur innovators Ecopel and House of Fluff to make bio-based next-gen fur materials. However, House of Fluff founder, Kym Canter, doesn't want to stop there; she has goals to go completely biodegradable and petroleum free.

> "We have always believed in good as a way to greatness. Sorona was the first big step towards creating a more earth-friendly animal-free fur. Our goal at House of Fluff is to go even farther to create the cleanest Biosynthetic textiles possible. We will not rest until we achieve the highest level of biodegradability and rid our textiles of petroleum, this is what we see as greatness!"

Kym Canter, Founder of House of Fluff

On the end-of-life spectrum, many bio-based polyesters that rely on chemistries similar to PET may be recyclable, but not biodegradable (see upper left quadrant of Figure 3). As discussed below in White Space 5, biodegradation, when done correctly, can mitigate textile pollution concerns. On this front, a class of biodegradable polyesters called polyhydroxyalkanoates (PHAs) may be a solution, as they can be produced from bio-based fermentation processes rather than fossil fuel derivatives (the ideal, upper right quadrant of Figure 3). This class of polymers is inherently biodegradable in many environments. Recent innovation from Mango Materials converts the greenhouse gas methane into PHA products via bacterial fermentation processes.[56] These raw polymer pellets can then be spun into textile fibers. Employing a similar technique is Newlight Technologies. They use their carbon negative, biodegradable PHA material to fabricate eyewear frames and next-gen leather goods, which can be purchased from their DTC arm, Covalent. (See more on PHAs in White Space 5).

55 DuPont, "The Sorona® Story," Sorona.com, accessed Sep 9, 2021. https://sorona.com/our-story

56 https://www.mangomaterials.com/

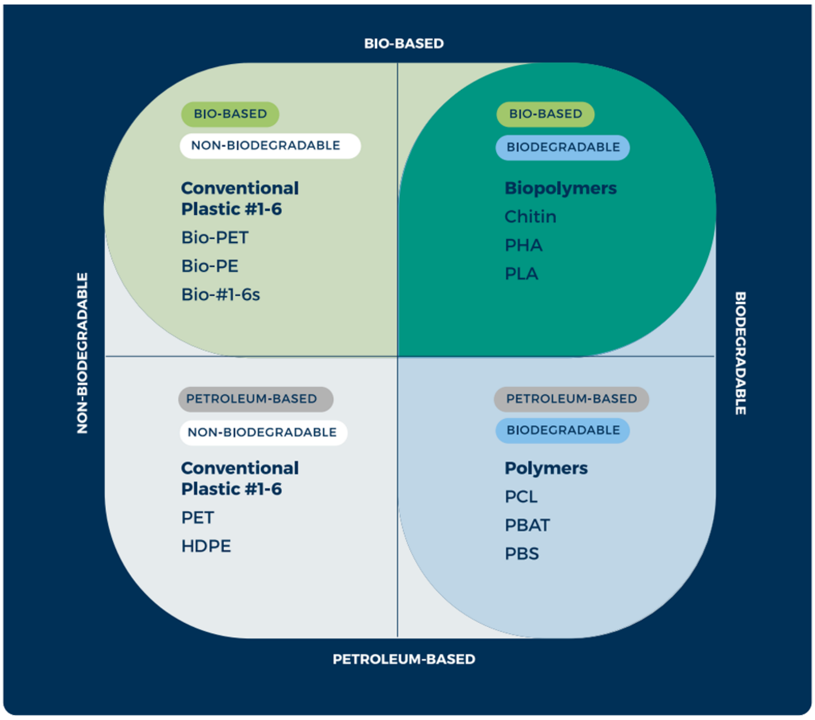

Figure 3. Landscape of plastic feedstocks across beginning-of-life (petroleum-based or bio-based) and end-of-life (biodegradable or non-biodegradable). Source: Closed Loop Partners, Navigating Plastic Alternatives in a Circular Economy, available at: https://www.closedlooppartners.com/research/navigating-plastic-alternatives-in-a-circular-economy/

Continued R&D and scale up is required to discover if PHAs or other promising chemistries can meet the broad applications needed in the next-gen materials space. There is promise that these bioplastics can be drop-in solutions, capable of being manufactured with the same equipment and processes as fossil-based synthetics.To allow synthetics to be an ideal solution in the textile bioeconomy, continued R&D for 100% bio-based, 100% biodegradable synthetic fibers is an area ripe for innovation.

FOLLOW-UP READING AND RESOURCES RELATED TO THIS TOPIC:

Material Innovation Initiative. Disruptive Textile Innovation Resources.
Available at: https://www.materialinnovation.org/disruptive-textile-innovation-resources

Navigating Plastic Alternatives in a Circular Economy.
Available at: https://www.closedlooppartners.com/research/navigating-plastic-alternatives-in-a-circular-economy/

Textile Exchange. Biosynthetics resources.
Available at: https://hub.textileexchange.org/learning-center/biosynthetics

Changing Markets Foundation. Fossil Fashion, and Synthetics Anonymous Reports.
Available at: https://changingmarkets.org/portfolio/fossil-fashion/

Alongside the role of synthetics such as PU and polyester as a versatile feedstock for next-gen materials, lies another important set of inputs: natural and semi-synthetic fibers and materials. Used primarily as fibers, these materials derived from plant matter are a significant portion of the textile industry. Plant fibers such as cotton and hemp account for ~30% of global fiber production, or over 30 million tonnes.[57] These fibers are extracted directly from the plant and mechanically processed into fibers and yarns. Semi-synthetics, or cellulosic fibers, also use plant-based inputs, but chemically regenerate the cellulose within the plant matter into new fibers. Cellulosics account for about 6% of global fiber production, with viscose (a.k.a. rayon) taking the primary share at over 5 million tonnes annually.[58]

Natural fibers and cellulosics

Similar to polyester, these plant-based fibers may find application in the next-gen materials space. Natural plant fibers are staple fibers (i.e., short, non-continuous), which means they won't make great replacements for silk, but they might apply to next-gen wool in the form of yarns, or as next-gen down in the form of insulating "fluff." Plant-based fibers may also be components for the coated textiles of next-gen leather. Cellulosic fibers are a bit more versatile - they can be filaments (i.e., long, continuous fibers), or staple fibers, which means they can find their way into nearly all of the next-gen material subcategories. Silky smooth lyocell (a form of rayon produced in a closed-loop chemical process)[59] and cupro (typically made from recycled cotton)[60] are the cellulosics most similar to silk.

Despite being "plant-based," both natural and cellulosic fibers still cause sustainability concerns. Although they aren't direct derivatives from fossil fuels like synthetics, natural fibers such as cotton can be associated with sustainability issues related to their agricultural source, namely land usage, water usage, and agrichemical usage. Land cleared for cotton agriculture can negatively affect local ecosystems and biodiversity and can also lead to soil depletion. Cotton currently uses 2.5% of the world's arable land, yet 10% of all agricultural chemicals such as those in pesticides and fertilisers.[61]

57 Textile Exchange, Preferred Fiber & Materials Market Report (2021): 9. https://textileexchange.org/wp-content/uploads/2021/08/Textile-Exchange_Preferred-Fiber-and-Materials-Market-Report_2021.pdf

58 Textile Exchange, Preferred Fiber & Materials Market Report (2021): 9. https://textileexchange.org/wp-content/uploads/2021/08/Textile-Exchange_Preferred-Fiber-and-Materials-Market-Report_2021.pdf

59 Sewport Support Team, "What is Lyocell Fabric: Properties, How it's Made and Where," sewport.com, accessed Sep 9, 2021. https://sewport.com/fabrics-directory/lyocell-fabric

60 Sewport Support Team, "What is Lyocell Fabric: Properties, How it's Made and Where," sewport.com, accessed Sep 9, 2021. https://sewport.com/fabrics-directory/lyocell-fabric

61 Cotton Up: Guide to Sourcing Sustainable Cotton, "Why Source Sustainable Cotton?" CottonUpGuide.org, accessed Sep 9, 2021. http://cottonupguide.org/why-source-sustainable-cotton/challenges-for-cotton/#1518784758976-1461109c-c091

Cellulosics on the other hand, rely primarily on wood pulp derived from virgin trees as a raw input. Over 200 million trees are logged annually to make cellulosic fibers.[62] As a result of this and other wood product industries, Canopy estimates that less than 20 percent of the world's ancient forests remain in tracts large enough to maintain biological diversity.[63] Water usage and chemical effluents are also of concern, primarily for viscose production, leading to widespread effects on local ecosystems and workers' health.[64] While some manufacturers employ regenerative agriculture practices and lower-impact tree sources such as eucalyptus, there is an opportunity to use other sources of raw cellulose to make these fibers.

Opportunities for sustainable biofeedstock:

The Laudes Foundation recently commissioned a report detailing possible sources of agricultural residues that could be employed by the textile industry in the form of natural fibers or cellulose fibers.[65] The requirements for the side streams highlighted in the study as candidate biomass for cellulosics include a minimum of 30% cellulose content and a minimum of one million tonnes of biomass annually. For natural fibers, the plant was previously identified as having extractable fibers with sufficiently long cellulose molecules to form robust textile fibers. Within these parameters, the authors found billions of tonnes of agricultural side streams that may be accessible for upcycling into usable fibers. Figure 4 shows some of the candidates with the largest available and viable volumes of agricultural waste that could be converted into cellulosic or natural fibers.

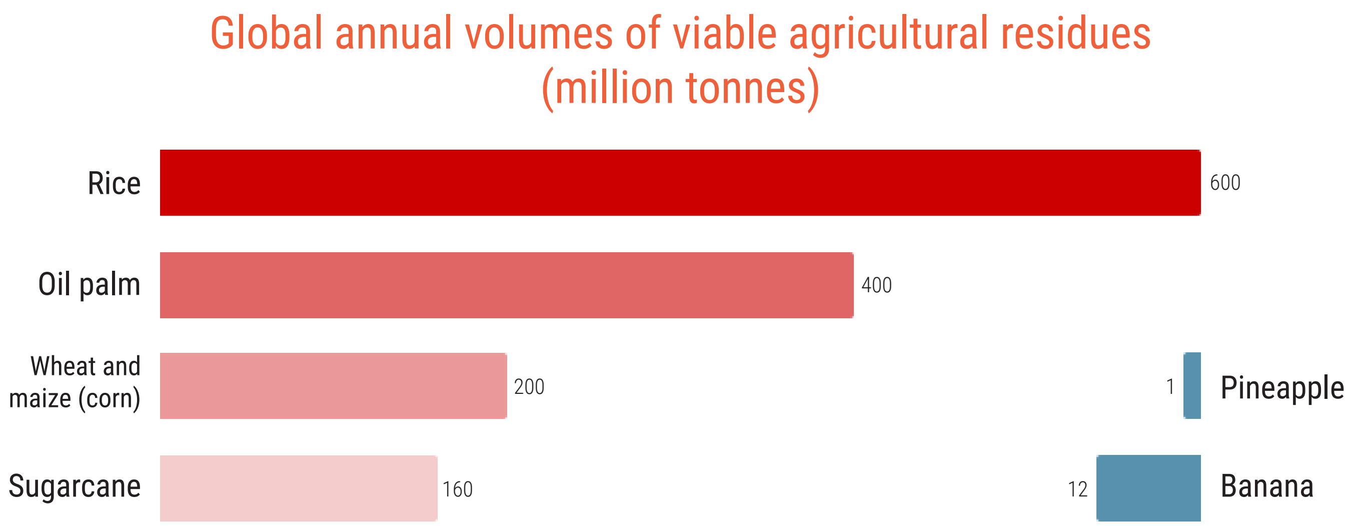

Figure 4. Current annual global supply of viable agricultural residue that may apply to cellulosics (left) and natural fibers (right). Data from: Institute for Sustainable Communities et al., Spinning Future Threads: The Potential of Agricultural Residues as Textile Fibre Feedstock (June 2021). Available at: https://laudes.h5mag.com/laudes/agri-waste_report_highlights/home/9656/agri_waste_report_2021_07_01.pdf

62 Canopy, "How we protect forests: CanopyStyle," CanopyPlanet.org, accessed Sep 10, 2021. https://canopyplanet.org/campaigns/canopystyle/

63 Canopy, "How we protect forests: CanopyStyle," CanopyPlanet.org, accessed Sep 10, 2021. https://canopyplanet.org/campaigns/canopystyle/

64 Changing Markets Foundation, Dirty Fashion: How pollution in the global textiles supply chain is making viscose toxic (June 2017): 1-35. http://changingmarkets.org/wp-content/uploads/2017/06/CHANGING_MARKETS_DIRTY_FASHION_REPORT_SPREAD_WEB.pdf

65 Institute for Sustainable Communities et al., Spinning Future Threads: The Potential of Agricultural Residues as Textile Fibre Feedstock (June 2021): 1-104. https://laudes.h5mag.com/laudes/agri-waste_report_highlights/home/9656/agri_waste_report_2021_07_01.pdf

As explained in our Bonus Section, there is much to learn from the alternative protein market as the next-gen material market continues to develop. Innovative food ingredients, for example, could lead to additional agricultural streams to consider for next-gen materials. One such example is the use of pea protein in animal-free burgers, milks, and more.[66] Because the protein is the primary product of the pea plant used in the food industry, the cellulose and other compounds may be left to waste. Scientists have found that legume waste can be processed into biodegradable materials such as plant pots,[67] and pea peel waste into biodegradable, plastic-like films.[68] With a planet to save and money to be made, waste valorization and agricultural upcycling for the creation of next-gen materials are smart and mission-aligned opportunities for alternative protein suppliers and innovators.

In addition to agricultural waste, currently underutilized, responsibly sourced virgin crops and wild biomass could form primary or secondary feed streams for the textile industry, diversifying the current material mix and potentially offering animal-free, next-gen solutions as well. Algae is emerging as an exciting feedstock, owing to its fast growth and unmatched carbon sequestration ability. Algae is 400 times more efficient than a tree at removing CO_2 from the atmosphere.[69] Trees can still be good resources for materials when their removal comes with added benefits. Instead of discarding or clearing biomass via controlled burns, forest waste could be valorized. Researchers have considered using such biomass to create alternative fuels, but this approach may simply contribute to increased emissions.[70] Processing biomass into new products such as next-gen materials could incentivize clearing dead forests while creating the opportunity to store carbon.

Algae is 400 times more efficient than a tree at removing CO_2 from the atmosphere.[69]

Trees can still be good resources for materials when their removal comes with added benefits. Instead of discarding or clearing biomass via controlled burns, forest waste could be valorized. Researchers have considered using such biomass to create alternative fuels, but this approach may simply contribute to increased emissions.[70] Processing biomass into new products such as next-gen materials could incentivize clearing dead forests while creating the opportunity to store carbon.

66 Vegcomomist: the vegan business magazine, "The Humble Pea Experiences Explosion Following Beyond Meat Phenomenon," vegconimist.com, Jul 11, 2019. https://vegconomist.com/market-and-trends/the-humble-pea-experiences-explosion-following-beyond-meat-phenomenon/

67 European Commission, Cordis EU research results, "Bio-products from legume waste," cordis.europa.eu, accessed Sep 10, 2021. https://cordis.europa.eu/article/id/170071-bioproducts-from-legume-waste

68 Upsana et al., "Utilization of pea industry waste for developing biodegradable product," Pantnagar Journal of Research 17, 3 (Sep-Dec 2019): 1-5. http://www.gbpuat.res.in/uploads/archive/17.3.13.pdf

69 Ben Lamm, "Algae might be a secret weapon to combatting climate change," qz.com, Oct 1, 2019. https://qz.com/1718988/algae-might-be-a-secret-weapon-to-combatting-climate-change/

70 Jane Braxton Little, "In California, A Push Grows to Turn Dead Trees into Biomass Energy," E360.yale.edu, May 19, 2020. https://e360.yale.edu/features/in-california-a-push-grows-to-turn-dead-trees-into-biomass-energy

Current trends

Some innovators have already capitalized on sustainable feed streams. Circular Systems uses agricultural waste, discarded textiles, and plastic waste to create a variety of novel fibers and yarns. Citizen Earth Group, recently selected as a finalist for the Microfiber Innovation Challenge, uses banana stem residues (of which ~12M tonnes are available globally, Figure 4) to create natural fibers.[71] AlgiKnit is producing novel, biodegradable yarns derived from kelp.

Pineapple leaf fibers harvested to make Piñatex® next-gen leather. Source: http://www.tactiletrends.com/home/sustainable-innovative-textiles-pinatex

"

TO MAKE PIÑATEX, WE UPCYCLE AGRICULTURAL WASTE AND TURN IT INTO A NON-WOVEN TEXTILE. BY DOING THIS, NOT ONLY ARE WE ALLEVIATING THE LOCAL PINEAPPLE FARMING COOPERATIVES WITH WASTE DISPOSAL ISSUES, WE ARE MORE IMPORTANTLY ABLE TO SAVE 8 KGS OF CO_2 -EQ FROM BEING EMITTED TO THE ATMOSPHERE FOR EVERY SQUARE METRE OF PIÑATEX PRODUCED.

"

MELANIE BROYÉ-ENGELKES, CEO OF ANANAS ANAM

71 ConservationX Labs, Microfiber Innovation Challenge, "Banana Fiber," accessed Sep 10, 2021. https://www.microfiberinnovation.org/innovation/banana-fiber

In the next-gen materials space, a number of innovators have employed these unique sources of biomass as an input to create animal-free alternatives:

- Ananas Anam (Piñatex®), next-gen material innovator, has partnered with agricultural powerhouse, Dole Sunshine Company, to transform pineapple waste into their products.[72]
- Flocus uses wild kapok fiber to create next-gen down insulation, as well as fibers and yarns. The kapok notably requires no pesticides, fertilizer, or irrigation unlike crops such as cotton. [73]
- Orange Fiber, next-gen silk innovator, uses residues from orange juice production to create cellulosic fibers
- Spinnova, next-gen wool innovator, has a versatile cellulosic processing technique that can employ a variety of agricultural residues. [74]

Vegea, Frumat, Beyond Leather, Fruitleather Rotterdam, Desserto, Fiquetex, Biophilica, Natural Fiber Welding, Oleago, and other next-gen leather innovators employ agricultural waste from apples, mangoes, cacti, municipal green waste, olives, and coconuts, among others. Although not typically used in the form of textiles, but rather as chopped fiber or fillers, these innovations showcase the potential of agricultural side streams as sustainable and innovative resources for material formulations. C-Combinator uses algae inputs to create next-gen leather and other products, showing further that non-fiber applications also apply to biofeedstocks.

In addition, several next-gen innovators use agricultural waste in bioprocessing techniques such as fermentation or mycelial growth to generate next-gen leather. Bolt Threads, MycoWorks, Phool, Ecovative Design, and other next-gen innovators feed agricultural waste to microbes and fungi in order to generate sheets of next-gen leather.

72 Ananas Anam, "Dole partners with Ananas Anam to achieve Zero Waste goal," Ananas-Anam.com, Aug 19, 2021. https://www.ananas-anam.com/dole-partners-with-ananas-anam-to-achieve-zero-waste-goal/

73 Vaude CSR Report, "Product: Kapok," csr-report.vaude.com, Aug 2, 2021. https://csr-report.vaude.com/gri-en/product/kapok.php

74 Spinnova, "From agricultural waste to textile fibre: Spinnova becomes part of Fortum's bio-based ecosystem," Spinnova.com, accessed Sep 10, 2021. https://spinnova.com/news/press-releases/from-agricultural-waste-to-textile-fibre-spinnova-becomes-part-of-fortums-bio-based-ecosystem/

75 Natalie Parletta, "Could Hemp Be The Next Big Thing In Sustainable Cotton, Fuel, Wood And Plastic?" Forbes.com, Jun 28, 2019. https://www.forbes.com/sites/natalieparletta/2019/06/28/could-hemp-be-the-next-big-thing-in-sustainable-cotton-fuel-wood-and-plastic/?sh=44d67c8221c2

Beyond identification of new biofeedstocks, we need processing innovation to make them work. For example, hemp has long been considered a sustainable, versatile crop, when farmed responsibly, capable of producing many products from its seed and fiber.[75] However, hemp fiber for textile applications suffers from several processing challenges, including degumming the "glue" that holds these bast fibers together in order for the individual fibers to be converted to yarn. Renaissance Fiber has developed an efficient, low impact, and cost-effective method for degumming hemp, which may enable increased use of this versatile plant.[76]

Summary for innovators from White Spaces 2, 3, and 4:

- Turn to the current marketplace of animal-free textile inputs (synthetics, cellulosics, and plant fibers).
- Innovate to make more sustainable, high performance versions of current feedstocks.
- Implement new feedstocks into formulations for next-gen materials, in order to eliminate our reliance on animal materials.

FOLLOW-UP READING AND RESOURCES RELATED TO THIS TOPIC:

Material Innovation Initiative. Disruptive Textile Innovation Resources.
Available at: https://www.materialinnovation.org/disruptive-textile-innovation-resources

Institute for Sustainable Communities et al., Spinning Future Threads: The Potential of Agricultural Residues as Textile Fibre Feedstock (June 2021).
Available at: https://laudes.h5mag.com/laudes/agri-waste_report_highlights/home/9656/agri_waste_report_2021_07_01.pdf

Canopy. CanopyStyle Guides and Reports.
Available at: https://canopyplanet.org/campaigns/canopystyle

Changing Markets Foundation. Dirty Fashion: the journey to responsible viscose production.
Available at: https://changingmarkets.org/portfolio/dirty-fashion/

Fashion for Good. Coming Full Circle: Innovating towards Sustainable Man-Made Cellulosic Fibres.
Available at: https://reports.fashionforgood.com/

76 Renaissance Fiber, "Our Technology: Degumming of Hemp Bast Fiber into Textile Fiber," renaissance-fiber.com, accessed Sep 10, 2021.
https://www.renaissance-fiber.com/our-fiber-processing

End-of-life options

Raw material choices for fashion, homegoods, or automotive applications are not only important for beginning-of-life sustainability considerations, they also determine the options for end-of-life pathways. Globally, around 92 million tonnes of textiles are discarded annually.[77] It is estimated that up to 30% of microplastic pollution may originate from textiles.[78] Material suppliers, designers, and manufacturers have a responsibility to understand the role of material selection in the fate of their product. Impending regulations may provide financial burden to manufacturer's without end-of-life strategies for their products, in the form of extended producer responsibility (EPR) fees.[79] Legislative proposals to offer import tax breaks for sustainable fibers may also make the sustainable choice the more affordable choice, forcing wider adoption of circular textiles.[80]

The options at the end of life for a textile product include:

- Recycling/reuse
  - recycled via traditional curbside recycling,
  - returned to the manufacturer for in-house recycling/reuse,
  - downcycled or upcycled into new product(s), including donation/resale/thrift, deadstock reuse, or textile waste valorization.
- Biodegradation
  - industrially composted,
  - anaerobically digested,
  - home composted.
- Other
  - discarded in a landfill,
  - burned for energy,
  - intentionally or unintentionally discarded in the open environment (e.g., marine environment, soil).

Ideally, materials and products should enter a circular economy, where resources can enter a closed-loop production, use, and disposal system, with minimal need for non-regenerative inputs or waste outputs. See Figure 5 for a generalized diagram of the circular economy for textiles.

77 Abigail Beall, "Why clothes are so hard to recycle," BBC.com/future, Jul 12, 2020. https://www.bbc.com/future/article/20200710-why-clothes-are-so-hard-to-recycle

78 IUCN, "Invisible plastic particles from textiles and tyres a major source of ocean pollution – IUCN study," IUCN.org, Feb 22, 2017. https://www.iucn.org/news/secretariat/201702/invisible-plastic-particles-textiles-and-tyres-major-source-ocean-pollution-%E2%80%93-iucn-study

79 Rachel Cernansky, "End-of-life regulation is coming for fashion," VogueBusiness.com/sustainability, Feb 4, 2021. https://www.voguebusiness.com/sustainability/end-of-life-regulation-is-coming-for-fashion

80 Rachel Cernansky, "What we need from policy: Fast-track sustainable materials," VogueBusiness.com/sustainability, Jan 21, 2021. https://www.voguebusiness.com/sustainability/what-we-need-from-policy-fast-track-sustainable-materials

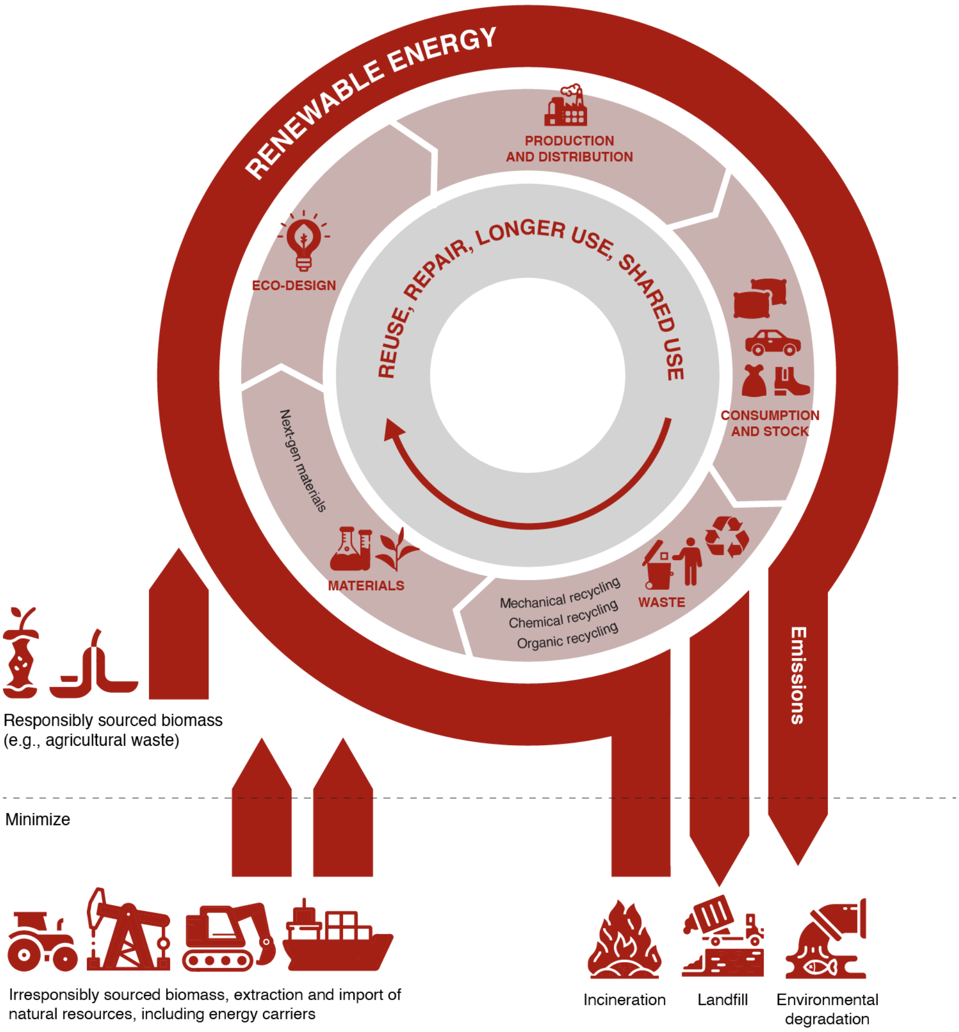

Figure 5. Circular economy concept for next-gen materials. Adapted from: European Environment Agency (EEA). Textiles and the environment in a circular economy (2019). Available at: https://www.researchgate.net/publication/344413782_Textiles_and_the_environment_in_a_circular_economy

Landfill disposal, burning for energy, and discarding in the open environment are the least "circular" pathways, and thus should generally be avoided as intentional end-of-life strategies. Unfortunately, these routes are currently the norm. According to the Ellen MacArthur Foundation, 73% of clothes are landfilled or incinerated.[81]

According to the Ellen MacArthur Foundation, 73% of clothes are landfilled or incinerated.[81]

Depending on the material and the disposal system, these pathways may contribute to greenhouse gas emissions and environmental pollution, and they offer minimal ways to recapture resources and value. It is estimated losses amount to $100B worth of materials each year.[82] However, in the current textile economy, mismanaged waste may still lead to materials and products in these less desirable scenarios, and may be important to consider when evaluating material choices.

81 Ellen MacArthur Foundation et al., A New Textiles Economy: Redesigning Fashion's Future, (2017): 20. https://emf.thirdlight.com/link/kccf8o3ldtmd-y7i1fx/@/preview/1?o

82 Ellen MacArthur Foundation et al., A New Textiles Economy: Redesigning Fashion's Future, (2017): 20. https://emf.thirdlight.com/link/kccf8o3ldtmd-y7i1fx/@/preview/1?o

Recycling

To date, recycling has been touted as the ideal circular solution to the end-of-life journey for materials and textiles. One of the most popular ESG goals made by fashion brands is increasing the use of recycled feedstock. However, to date only 1% of all textiles are recycled, leading many to question if these ESG goals will actually be met by circular textiles. (See White Space 3.)

Roadblocks to recycling realization include:

- Lack of consumer awareness and incentives for recycling textiles. Many users are unaware they can recycle their textiles, don't know where or how to do it, and typically won't receive buybacks or other incentives for "doing the right thing."
- Lack of infrastructure. Municipal recycling centers are equipped to handle specific materials and products, and textiles (of any type) are typically not in that list. Specific textile processing centers are few and far between and consumers lack access.
- Mixed and hybrid textiles. It is extremely difficult to separate and then recycle textiles made with mixed materials, such as a cotton-polyester blend fabric.
- Quality reduction as a result of recycling. Regardless of whether the material is cotton or polyester, traditional mechanical recycling shortens fiber lengths. Mechanical recycling can also degrade the polymer molecules, leading to lower quality products, and limitations on the number of times a material can be recycled.[83]
- Lack of profit. Because of the reasons above, recycling often turns very little profit or actually loses money. Without government funding, many recycling centers close.

Although individual material manufacturers, brands, and retailers have begun to implement incentives to return goods at their end of life for industrial recycling or reuse,[84] there has yet to be widespread adoption of this method. The burden is still placed on consumers to do their research and make every effort to do the right thing. Textile-to-textile recycling has emerged with new techniques to enable collection, separation, sorting, and regeneration of inputs.[85] Chemical recycling, whereby materials are dissolved or disassembled into their chemical building blocks, has also emerged as a potential solution for synthetic textile waste.[86] These techniques may enable virtually infinite recycling loops that generate high quality feedstock. Continued R&D and scale-up are necessary before such technology can process meaningful amounts of waste without prohibitive cost.

Perhaps most importantly, there is a big difference between being *recyclable* and *actually being recycled*. All recycling technologies rely on a first step: collection and sorting of waste. Without a global infrastructure overhaul to enable facile, widespread textile recycling, this pathway won't be a meaningful way out of our sustainability crisis.

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83 Design for Longevity, "Close the Loop," DesignForLongevity.com, accessed Sep 29, 2021. https://designforlongevity.com/articles/close-the-loop

84 Elizabeth Segran, "Madewell, Patagonia, and Eileen Fisher want to buy your old clothes," FastCompany.com, Jun 26, 2019. https://www.fastcompany.com/90368774/madewell-patagonia-and-eileen-fisher-want-to-buy-your-old-clothes

85 Ben Smee, "Recycling textile waste: 'A solution exists, we can't go backwards'," TheGuardian.com, May 29, 2021. https://www.theguardian.com/environment/2021/may/30/recycling-textile-waste-a-solution-exists-we-cant-go-backwards; Sourcing Journal, "Recover Scales Textile-to-Textile Recycling to Meet Growing Demand," SourcingJournal.com, Jul 14, 2021. https://sourcingjournal.com/topics/sustainability/recover-recycled-cotton-manufacturing-sustainability-demand-290180/

86 Nina Notman, "Recycling clothing the chemical way," ChemistryWorld.com, Jan 27, 2020. https://www.chemistryworld.com/features/recycling-clothing-the-chemical-way/4010988.article; Soumyadeep Saha, "Textile Recycling: The Chemical Recycling Process of Textiles," OnlineClothingStudy.com, Aug 25, 2020. https://www.onlineclothingstudy.com/2020/08/textile-recycling-chemical-recycling.html

Biodegradation

The circular economy for textiles also includes reuse and organic recycling (i.e., biodegradation).

These two pathways have historically been considered diametrically opposed. Materials and products capable of reuse must be durable and long-lasting, while materials capable of biodegradation must be able to break down in a reasonable timeframe. This leads many to believe that biodegradable products are inherently not durable, and are thus suited for single-use or low performance applications.

However, there are a few considerations to make for materials intended primarily for the fashion industry.

- Clothing items are not in use for very long, thus the bar for durability may be lower than we currently expect.
- Biodegradation occurs in specific environments and on specific timescales, and thus it is possible for a material to be both durable and capable of biodegradation at end-of-life.

Despite recent pushes to rethink consumption patterns towards "slow fashion," the average consumer wears an item of clothing fewer than 10 times.[87]

Changing styles, tastes, and sizes of consumers drive some of this trend.[88] The International Fabricare Institute expects the average lifetime of the majority of textile article categories to vary from 1-3 years, with only a handful of garments expected to last over 5 years.[89] Knowing that these garments aren't recycled means they mostly end up in landfills. That means products intended to be "durable" and "long-lasting" may still be discarded relatively quickly, and left to persist in landfills or migrate to our oceans. Although reuse via donating/ reselling can extend the life of a material by approximately 2 years,[90] eventually the product or material will meet the end of its useful life. While we wait to see if consumer habits evolve, biodegradation may offer additional pathways to improve the circularity of materials.

87 Elizabeth Segran, "Madewell, Patagonia, and Eileen Fisher want to buy your old clothes," FastCompany.com, Jun 26, 2019. https://www.fastcompany.com/90368774/madewell-patagonia-and-eileen-fisher-want-to-buy-your-old-clothes; CBS News, "Fast fashion in the U.S. is fueling an environmental disaster in Ghana," CBSNews.com, Sep 18, 2021. https://www.cbsnews.com/news/ghana-fast-fashion-environmental-disaster/

88 Abigail Beall, "Why clothes are so hard to recycle," BBC.com/future, Jul 12, 2020. https://www.bbc.com/future/article/20200710-why-clothes-are-so-hard-to-recycle

89 International Fabricare Institute (IFI), Table I: Average Life Expectancy of Textile Items in Years, no date. https://www.textilerestorations.com/lifeexpectancy.pdf

90 Elizabeth Segran, "Madewell, Patagonia, and Eileen Fisher want to buy your old clothes," FastCompany.com, Jun 26, 2019. https://www.fastcompany.com/90368774/madewell-patagonia-and-eileen-fisher-want-to-buy-your-old-clothes

What is biodegradation? Certain polymeric textile materials are capable of being broken down into smaller fragments and molecules via environmental weathering and the activity of organisms such as microbes and fungi. The material can thus be “mineralized” into carbon resources that reenter the bioeconomy. In oxygen-rich composting environments, the primary breakdown products are carbon-rich humus, CO_2, and water.[91] These are key nutrients for plants to thrive. Importantly, these emissions from bio-based materials are part of the biogenic carbon cycle, unlike emissions from fossil fuels which introduce “new,” anthropogenic carbon into the atmosphere.[92]

In a landfill, a different breakdown process occurs which emits the greenhouse gas methane (CH_4), in addition to CO_2. Methane is more short lived than CO_2, but is estimated to be 25 times more potent for warming threats.[93] In the United States, about 70% of landfills capture the methane and either burn it or use it for energy.[94]

It is important to understand that there is no generally accepted definition or measurement of biodegradation. Biodegradation can occur via different mechanisms, in different environments, at different timescales, and with different degradation byproducts. It is important to ensure that materials are not broken down into harmful substances, or fragmented into persistent microplastics. Even for the same class of material (e.g., PLA), variations such as crystallinity and molecular size can affect biodegradation rates.[95] Therefore a claim that a material is “biodegradable” is best supported with data. International standards have been developed for biodegradable synthetics that apply specific conditions and requirements such as degradation timelines and testing for soil toxicity.[96] The most common intentional environments for biodegradation are industrial composting, anaerobic digestion facilities, and home composting. Unintentional environments such as soil or marine, are also contemplated for the case of mismanaged waste.

91 Nezha T. Joutey et al., “Biodegradation: Involved Microorganisms and Genetically Engineered Microorganisms,” Biodegradation - Life of Science, Rolando Chamy, editor, Jun 14, 2013. https://www.intechopen.com/chapters/45093;
Robert Pavlis, “Does Composting Contribute to Climate Change?” GardenMyths.com, accessed Sep 29, 2021. https://www.gardenmyths.com/composting-climate-change/

92 US Composting Council, “Greenhouse Gases and the Role of Composting: A Primer for Compost Producers,” USCC Factsheet (2008): 1-3. https://www.sanjoseca.gov/home/showpublisheddocument?id=198

93 United States Environmental Protection Agency (EPA), “Overview of Greenhouse Gases,” EPA.gov, accessed Sep 21, 2021. https://www.epa.gov/ghgemissions/overview-greenhouse-gases;
United States Environmental Protection Agency (EPA), “Basic Information about Landfill Gas,” EPA.gov, accessed Sep 21, 2021. https://www.epa.gov/lmop/basic-information-about-landfill-gas

94 Chris Keenan, “Biodegradable Products Cause Greenhouse Gas Emissions,” CleanTechnica.com, Jun 2, 2011. https://cleantechnica.com/2011/06/02/biodegradable-products-cause-greenhouse-gas-emissions/

95 Kyungjun Min et al., “Ranking environmental degradation trends of plastic marine debris based on physical properties and molecular structure,” Nature Communications 11, 727 (2020). https://www.nature.com/articles/s41467-020-14538-z

96 Annemette Kjeldsen et al., A Review of Standards for Biodegradable Plastics, Industrial Biotechnology Innovation Centre, no date, 1-33. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/817684/review-standards-for-biodegradable-plastics-IBioIC.pdf

Municipal or private biodegradation services are typically far rarer than recycling services, so materials relegated to this pathway suffer many of the same issues as recycling due to the infrastructure gap. In the United States in 2018, about 9% of all plastics were recycled and about 4% of food scraps were composted.[97] Yard trimmings were composted at a rate of 63%, however, showing promise for this avenue.[98] As with recycling, these materials still require collection, (sometimes) sorting, and processing. Home composting requires the time and attention of the consumer, but is relatively accessible and affordable. It is preferable, of course, that materials don't end up in landfills, in open soil, or in the ocean, but enabling materials to safely and quickly break down even in these environments may prevent persistent pollution.

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The conditions for use of a textile article are very different from the composting or open-environment conditions contemplated during biodegradation processes. This is why common biodegradable materials such as cotton can survive wearing and laundering processes over a lifetime of years to decades, but can break down in compost conditions on the order of weeks.[99] Indeed, it is possible for material innovators to optimize for both durability and end-of-life biodegradation.

97 United States Environmental Protection Agency (EPA), "National Overview: Facts and Figures on Materials, Wastes and Recycling," EPA.gov, accessed Sep 21, 2021. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials#:~:text=In%202005%20it%20was%2062,percent%20(2.6%20million%20tons)

98 United States Environmental Protection Agency (EPA), "National Overview: Facts and Figures on Materials, Wastes and Recycling," EPA.gov, accessed Sep 21, 2021. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials#:~:text=In%202005%20it%20was%2062,percent%20(2.6%20million%20tons)

99 George Arnett, "How quickly do fashion materials biodegrade?" VogueBusiness.com/sustainability, Nov 29, 2019. https://www.voguebusiness.com/sustainability/fashion-biodegradable-material-circularity-cotton

White space: versatile end-of-life strategies

Clearly there are multiple end-of-life strategies for next-gen materials, each with challenges and opportunities. Which end-of-life scenario will be "the winner?" Where should material innovators place their bets?

An attractive solution to these many issues may be materials that are versatile in their end-of-life strategy. Ideally, materials will be durable enough for long-term use or reuse, capable of being recycled, and capable of safe biodegradation in many possible environments. This way the lowest burden is placed upon the consumer for end-of-life management. When engineered and maintained appropriately, the product can be reused/donated/resold. If consumers have easy access to recycling or composting, they can use these pathways. But even if that material leaks into the open environment, biodegradation can reduce long-term pollution associated with waste. Fortunately, we are already seeing innovation in raw materials choices that may meet this lofty goal.

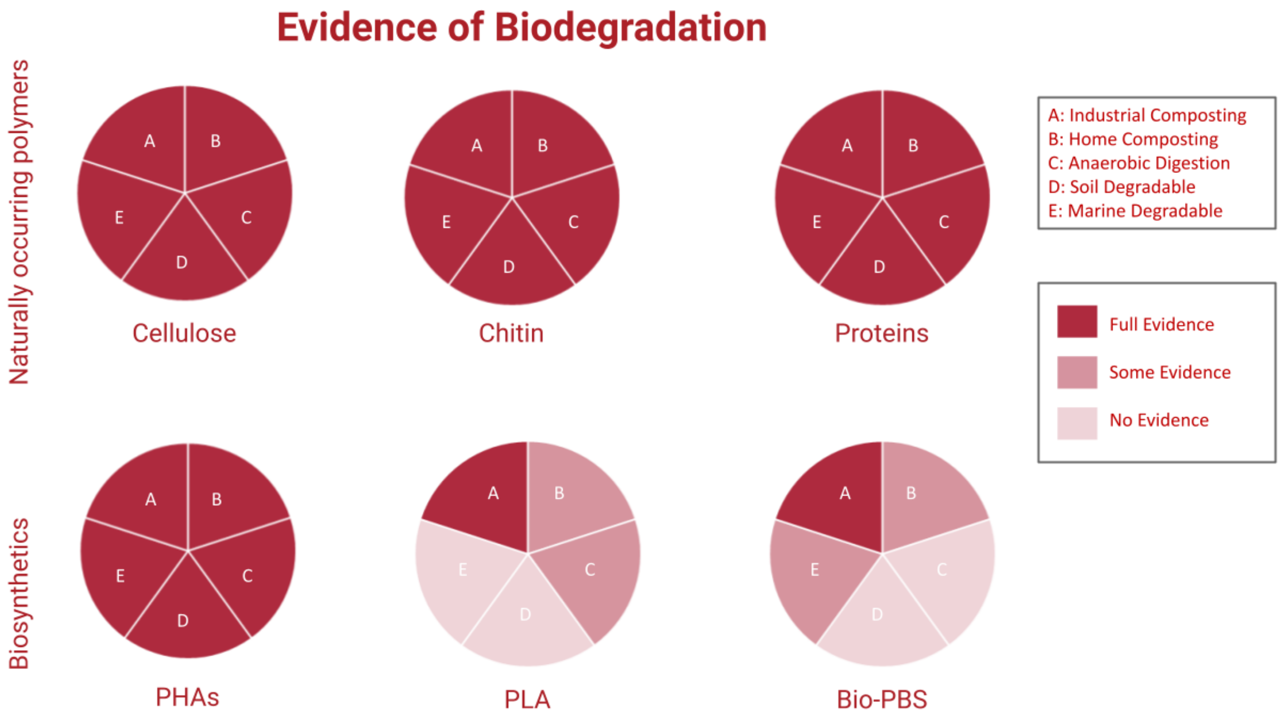

Figure 6. Promising natural or synthetic feedstock with multiple biodegradation pathways. Adapted from Closed Loop Partners, Navigating Plastic Alternatives in a Circular Economy, available at: https://www.closedlooppartners.com/research/navigating-plastic-alternatives-in-a-circular-economy/

Naturally occurring polymers, such as cellulose, chitin, and proteins, can be derived from plants, microbes, and fungi and formed into fibers or other material components. Naturally occurring polymers can be mechanically recycled (e.g., recycled cotton) or chemically regenerated into new fibers (e.g., cellulosics). Importantly, these naturally occurring polymers are typically biodegradable in all major environments: industrial composting, home composting, anaerobic digestion, soil, or the marine environment (Figure 6).[100] Lenzing's cellulosic products, for example, have been certified biodegradable in soil, compost, freshwater, and marine water.[101] Like all textile materials, care must be taken to determine if processing or additives reduce the ability or rate of degradation.

100 Closed Loop Partners et al., Navigating Plastic Alternatives in a Circular Economy, available at: https://www.closedlooppartners.com/research/navigating-plastic-alternatives-in-a-circular-economy

101 Chris Remington, "Lenzing fibres certified biodegradable," EcoTextile.com, Sep 5, 2019. https://www.ecotextile.com/2019090524616/materials-production-news/lenzing-fibres-certified-biodegradable.html

Several synthetic options for textiles and materials offer multiple end-of-life pathways. For example, polylactic acid (PLA) is currently the most popular player in bio-based, degradable plastics. Typically used in food and beverage packaging applications, recent advancements in fiber spinning may enable 100% PLA garments.[102] Derived from fermented starches such as corn, PLA is 100% bio-based. It is also capable of industrial composting, and for certain grades, compostable at home or in anaerobic digestion. In some instances, PLA can also be recycled, but typically not in the average recycling facility where it can contaminate traditional plastic feed streams.[103] Unfortunately, PLA doesn't degrade easily in soil or the marine environment.[104] When PLA leaks into the environment, it can degrade much like traditional plastics and create macro- and microplastic pollution. Although not perfectly pathway-independent, PLA was one of the first successful biosynthetics to take the stage.

Another biosynthetic worth noting for textile applications is bio-based polybutylene succinate (bio-PBS), derived from fermentation processes. Similar to PLA, bio-PBS may be recyclable in special instances. It biodegrades in industrial composting facilities, and there is some evidence of biodegradation in the soil or home composting (Figure 6).[105] Kintra Fibers is an innovator of bio-PBS fibers, currently partnered with Pangaia to bring these fibers to market.[106] While touted as a replacement for polyester, it is possible these novel fibers could be applied to next-gen silk, wool, down, or fur.

One of the most promising classes of bio-based, biodegradable synthetics derived from fermentation processes are polyhydroxyalkanoates (PHAs).

As a thermoplastic material like PLA and bio-PBS, PHAs have the capability to be mechanically recycled, although only in special circumstances. However, PHAs are unique as the only class of synthetic polymers that has been shown to degrade in all major environments: industrial composting, home composting, anaerobic digestion, soil, or the marine environment (Figure 6).[107] In the past, PHAs were unable to compete with fossil-based plastics, because of small volumes and high prices. With continued innovation and current sustainability demands, the time may be right for PHAs to succeed.[108]

Strategies exist to induce biodegradation in traditional synthetics such as polyester. However, it is critical that these approaches do not fragment the plastic and increase microplastic pollution in the environment, and also do not break down the plastic into harmful byproducts.

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102 Business Wire, "A Clothing That Was Planted: Xtep Launched New PLA T-shirts," BusinessWire.com, Jun 4, 2021. https://www.businesswire.com/news/home/20210604005128/en/%C2%A0A-Clothing-That-Was-Planted%EF%BC%9AXtep-Launched-New-PLA-T-shirts;
València Parc Tecnològic and FIBFAB consortium, "FIBFAB Project: Industrialization of biobased textile fabrics for clothing applications," fibfab-project.eu, accessed Sep 10, 2021. https://fibfab-project.eu/

103 Scientific American, "The Environmental Impact of Corn-Based Plastics," ScientificAmerican.com, Jul 1, 2008. https://www.scientificamerican.com/article/environmental-impact-of-corn-based-plastics/

104 Closed Loop Partners et al., Navigating Plastic Alternatives in a Circular Economy, available at: https://www.closedlooppartners.com/research/navigating-plastic-alternatives-in-a-circular-economy/

105 Closed Loop Partners et al., Navigating Plastic Alternatives in a Circular Economy, available at: https://www.closedlooppartners.com/research/navigating-plastic-alternatives-in-a-circular-economy/

106 Pangaia blogs, "We're creating Biodegradable Polyester with Kintra Fibers, here's how," ThePangaia.com, accessed Sep 21, 2021. https://thepangaia.com/blogs/editorials/pangaia-x-kintra-biodegradable-polyester

107 Closed Loop Partners et al., Navigating Plastic Alternatives in a Circular Economy, available at: https://www.closedlooppartners.com/research/navigating-plastic-alternatives-in-a-circular-economy/

108 Alexander H. Tullo, "Will the biodegradable plastic PHA finally deliver?" CEN.ACS.org, Jun 13, 2021. https://cen.acs.org/business/biobased-chemicals/biodegradable-plastic-PHA-finally-deliver/99/i22

Next-gen opportunities:

Many next-gen innovators rely on naturally occurring, universally biodegradable materials based on cellulose/starch, chitin, or proteins. Cellulose and starches are the primary composition of the agricultural virgin or waste products employed by numerous next-gen innovators. (See White Space 4.) Chitin is the primary component of hyphae filaments which form mycelium leather. Material companies in this space include: Bolt Threads Mylo™, Ecovative Design Forager™ Hides, Mogu, MYCL Mylea™, MycoWorks Reishi™, Mylium, Neffa MycoTEX®, and Spora Biotech Sporatex. Recombinant silk proteins form the basis of many next-gen silk innovators (AMSilk Biosteel®, Bolt Threads Microsilk™, Seevix SVX™, Spiber Brewed Protein™), and recombinant collagen is the focus for next-gen leather innovators Modern Meadow and Provenance Bio. It is reasonable to expect that these materials will breakdown via all degradation pathways, but innovators will still need to conduct testing to ensure that processing or additives do not disrupt these pathways.

Biodegradable synthetics, on the other hand, have seen less adoption by next-gen innovators to date. PLA has been employed by Ananas Anam as a component of their Piñatex next-gen leather. We have not seen any innovators employ bio-PBS or PHAs for fibrous next-gen materials such as replacements for silk, wool, fur, or down. Fashion for Good is leading a collaborative program to solve technical challenges associated with forming PHAs into fibers and textiles.[109] Newlight Technologies is a member of this program, and has used their PHA-based AirCarbon material as next-gen leather, with products available for purchase from their DTC arm, Covalent.

Excitingly, the AirCarbon material has been verified to be home compostable[110] and can biodegrade in ocean water conditions on a similar timescale to cellulose, according to ASTM D6691.[111] The AirCarbon material is also dishwasher-safe and reusable for food applications, and thus possible for use as a launderable textile. The products can also be shipped back to Newlight for internal recycling. This material shows promise at achieving the desired goal of end-of-life versatility.

109 Fibre2Fashion.com, “Fashion for Good launches Renewable Carbon Textiles project,” Jun 2021. https://www.fibre2fashion.com/news/textile-news/fashion-for-good-launches-renewable-carbon-textiles-project-274527-newsdetails.htm

110 Newlight Technologies, Inc., AirCarbon, accessed Sep 22, 2021. https://www.newlight.com/

111 Newlight Technologies, Inc., “Products,” Newlight.com, accessed Sep 22, 2021. https://www.newlight.com/products

> *THE IDEA BEHIND AIRCARBON WAS LOOKING TO NATURE TO SEE HOW IT APPROACHES GREENHOUSE GAS. WHAT WE FOUND WAS THAT NATURE SEES GREENHOUSE GAS AS A RESOURCE, AND USES IT AS THE BACKBONE FOR MOST OF THE GROWTH WE SEE IN THE NATURAL WORLD: NEW TREE LEAF GROWTH, CORAL REEF FORMATION, AND COUNTLESS OTHER PROCESSES. ALL OF THESE ARE CARBON-NEGATIVE PROCESSES. SO IN 2003 WE SET OUT TO DO SOMETHING SIMILAR. AFTER 18 YEARS OF DEVELOPMENT, WE HAD SCALED UP A PROCESS FOUND IN THE OCEAN THAT USES RENEWABLE POWER AND MICROORGANISMS TO TURN AIR AND GREENHOUSE GAS INTO A CARBON-NEGATIVE BIOMATERIAL CALLED PHB--PHB IS MADE IN ALMOST ALL LIVING THINGS, INCLUDING THE HUMAN BODY, AND CAN BE USED TO REPLACE PLASTIC AND LEATHER--WE CALL IT AIRCARBON.*
>
> *MARK HERREMA, CEO OF NEWLIGHT TECHNOLOGIES, LLC*

Below are a few other examples of next-gen innovators employing versatile end-of-life strategies:

- Natural Fiber Welding. Their Mirum next-gen leather is a part of a buyback program.[112] The material can be formed into regrind and re-introduced into the manufacturing process. Their 100% bio-based formulation is capable of biodegradation.[113]
- Spinnova. Their cellulosic fibers, finding their application in next-gen wool, are in-house recyclable, as well as biodegradable on the order of a few months in marine and other natural environments.[114]
- Beyond Leather. Their Leap next-gen leather, derived from apple waste and other bio-based ingredients, is designed to be separated at end of life. Components are biodegradable or recyclable.[115]

112 Natural Fiber Welding, "Natural Fiber Welding Launches Circular Buy-Back Program with New Woolly Made MIRUM® Wallets," blog.NaturalFiberWelding.com, Sep 3, 2021. https://blog.naturalfiberwelding.com/woolly-made-mirum-accessories

113 Natural Fiber Welding, "Frequently Asked Questions About MIRUM®," Mirum.NaturalFiberWelding.com, accessed Sep 22, 2021. https://mirum.naturalfiberwelding.com/faq?hsLang=en#recyclable-circular-mirum

114 Spinnova, "Sustainability," Spinnova.com, accessed Sep 22, 2021. https://spinnova.com/sustainability/

115 Beyond Leather: Leap, "Frequently Asked Questions," Explore-Leap.com, accessed Sep 22, 2021. https://www.explore-leap.com/faq

Innovation to address end-of-life can make a big impact in sustainable textiles. Designing multiple pathways for managing waste from the outset is an attractive and relatively unexplored area for consideration by the next-gen materials industry.

FOLLOW-UP READING AND RESOURCES RELATED TO THIS TOPIC:

Biomimicry Institute. The Nature of Fashion.
Available at: https://biomimicry.org/thenatureoffashion/

Ellen MacArthur Foundation. A New Textiles Economy and related resources.
Available at: https://ellenmacarthurfoundation.org/a-new-textiles-economy

Navigating Plastic Alternatives in a Circular Economy.
Available at: https://www.closedlooppartners.com/research/navigating-plastic-alternatives-in-a-circular-economy/

Hohenstein Institute. Biodegradation resources and testing.
Available at: https://www.c2ccertified.org/

Cradle to Cradle Innovation Institute. Certification and resources.
Available at: https://reports.fashionforgood.com/

Fashion for Good. C2C Certified project resources.
Available at: https://fashionforgood.com/news/resource-library/c2c-certified/

6. MATERIALS SCIENCE DONE RIGHT

Bottom-up material design

It may seem obvious, but understanding the core principles of materials science and engineering and applying them during the R&D phase of materials development are critical to the success of a novel material. These core principles involve the intersection of composition, structure, processing, properties, and performance - often shortened to structure-property relationships. As illustrated in Figure 7, it is important to understand performance requirements, the specific material properties that inform this performance, and the ability to tune the knobs of composition, structure, and processing to achieve the desired result.

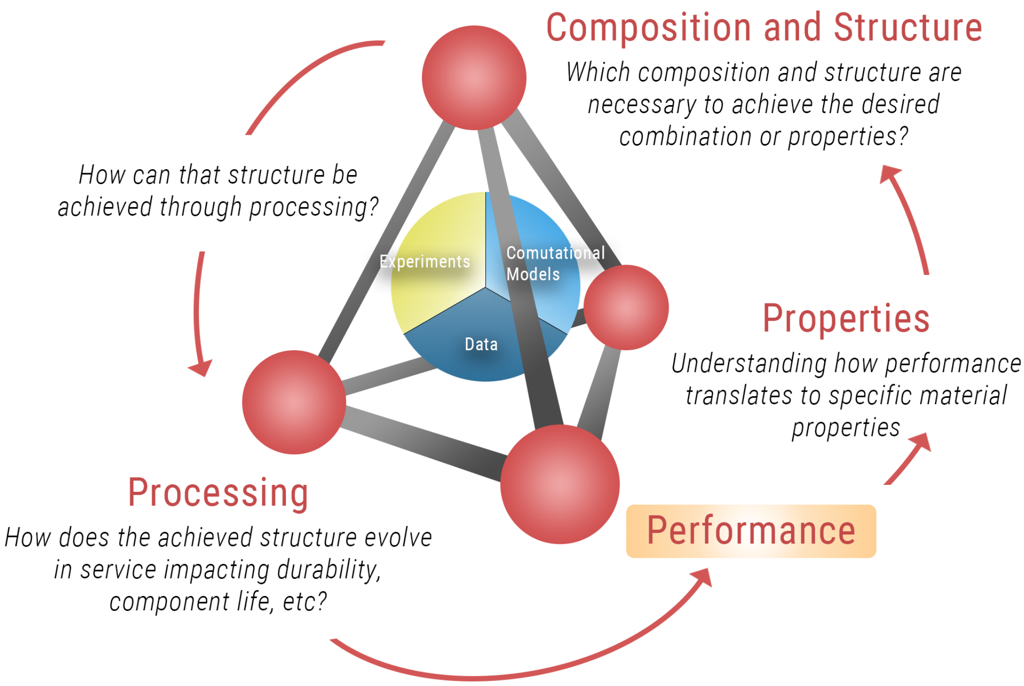

Figure 7. The core principles of materials science and engineering. Adapted from: https://gems.matse.illinois.edu/educators/

The unique properties of animal-derived materials such as leather, silk, wool, fur, down, and exotic skins are primarily reliant on their biological assembly into hierarchical structures. In other words, as you traverse the length scales of these materials, each level of the structure plays an important role in the end properties of the material. Beginning with the smallest length scale of the amino acid sequences that comprise the protein chains, on to the formation and assembly of these proteins into structures such as helixes or crystalline sheets, then larger still to the packing of these proteins into fibrils of various sizes, and up to the largest scale macrofibers - each level of the hierarchy dictates the performance of the material. An example of this hierarchical structure is shown in Figure 8, for a keratin-based wool fiber. Wool's unique thermal regulation, stretch, and shape-retention properties are dependent upon this intricate assembly of the fiber.

"

The more our world functions like the natural world, the more likely we are to endure on this home that is ours, but not ours alone.[116]

"

Janine Benyus, author and co-founder of the Biomimicry Institute and Biomimicry 3.8

Using the principles of biomimicry, scientists can thoughtfully design animal-free materials using the knowledge of how assembly influences performance. This can be thought of as "bottom-up" materials design. This is in contrast to "top-down" materials design, whereby material manufacturers start with something that "looks" or "feels" like the incumbent material. Although the top-down approach can sometimes be simpler, materials that only aesthetically mimic incumbent materials, without consideration of the interdependence of structure and performance, may come up short on adoption by the textile industry. It is much more difficult to backfill critical performance metrics, than to seek them intentionally from the start of material development. This is not to say that aesthetics are unimportant, but rather that aesthetics, performance, and sustainability should be equally considered when designing novel next-gen materials.

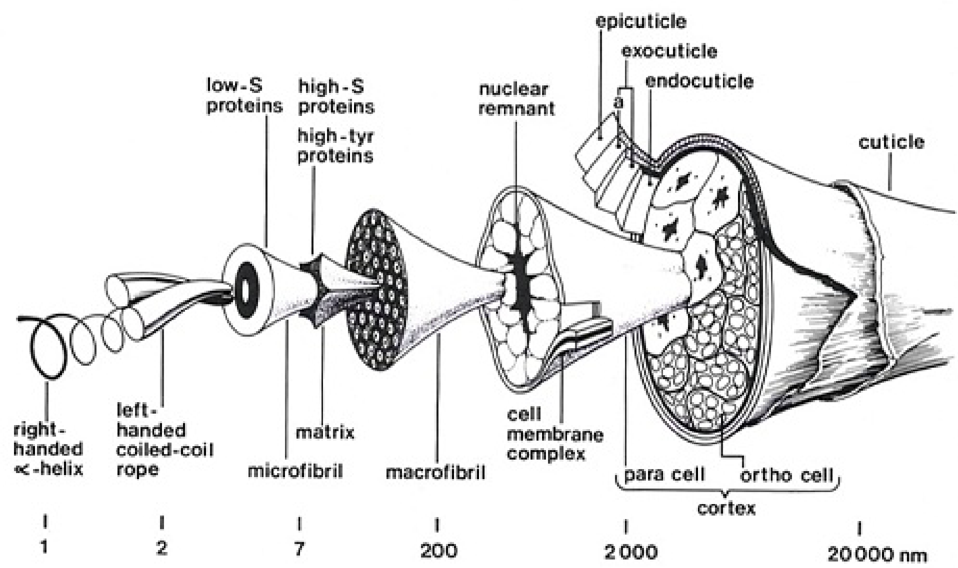

Figure 8. Diagram of the hierarchical structure of wool fibers, spanning the smallest individual proteins (left) to the macroscopic, layered fiber (right). Source: CSIRO, Schematic diagram of the wool fibre drawn by Bruce Fraser, Tom MacRae and colleagues. https://csiropedia.csiro.au/wool-fibre-structure/

116 Janine M. Benyus, Biomimicry: Innovation Inspired by Nature, New York: Quill (1997).

One of the methods for bottom-up design is to employ recombinant protein synthesis to create specific animal proteins without farming and exploiting animals. With recombinant protein synthesis, microbes are genetically modified to act as protein factories, and the resulting proteins can then be harvested and processed into fibers or sheets. Instead of microbes, whole plants can be engineered to produce the foreign protein in some instances. Another approach is to grow mammalian cells into tissue constructs, effectively growing the "skin" without growing the whole animal. The lab-grown hide can then be processed and tanned similar to incumbent leather.

Mycelial growth is also an attractive bottom-up method to mimic the structure of leather. The hyphae filaments of mycelium mimic the collagen fibers of animal-based leather. Interestingly, even though these mycelium leathers are formed primarily from the polymer chitin rather than collagen, they can be tanned in similar ways as animal-based leather. This allows mycelium leathers to look and even smell like the incumbent materials.

Each of these bottom-up techniques show great promise to directly mimic the formulation and structure of target incumbents. However, there are many challenges associated with these novel biotechnology methods that need to be overcome to see these materials at scale and price parity. (See White Space 7.) Currently, we see the most activity for these approaches in next-gen silk and next-gen leather.

Importantly, innovators can also use the bottom-up design approach to fine-tune material characteristics to exceed those of the incumbent. For example, next-gen silk innovator Spiber found that early iterations of their Brewed Protein product mimicked not only positive attributes of spider silk, but also some of the less desirable characteristics, namely a supercontraction phenomenon that leads to extreme shrinkage of the yarns and textiles with exposure to water. By editing the recombinant protein structure produced by their fermentation process, Spiber "engineered-out" this issue.[117]

Not all materials need to be grown in a laboratory in order to successfully employ bottom-up materials design. Advancements in polymer chemistry and composite engineering use the lessons of nature and apply them to man-made materials.

For example, cellulosic fibers can be processed to have similar structures and properties to those of native silk. Just as the animal extrudes the silk solution, forming aligned crystalline structures within continuous fibers, cellulosic fibers can also be extruded from solution such that cellulose crystals are aligned to create smooth filaments. Cellulosics such as lyocell that are processed in this way can have comparable physical properties to silk derived from silkworms.[118]

In another example, Natural Fiber Welding relies on engineering principles originally destined for composites in aerospace applications to create structures and formulations that mimic the properties of animal-based leather.

117 Katsumori Matsuoka, "Can Spiber make spider silk-like materials a reality?" CEN.acs.org, Apr 11, 2021. https://cen.acs.org/materials/biomaterials/Spiber-make-spider-silk-like/99/i13

118 Catarina Felgueiras et al., "Trends on the Cellulose-Based Textiles: Raw Materials and Technologies," Frontiers in Bioengineering and Biotechnology, Mar 29, 2021. https://www.frontiersin.org/articles/10.3389/fbioe.2021.608826/full

The structure-property relationships of incumbent animal-derived materials are summarized below:

- Leather and exotic skins rely upon the interconnected network of collagen fibrils and their orientation within the skin structure to create tough, flexible sheets.[119]
- Silk relies upon the assembly of the fibroin (for silkworms) or spidroin (for spiders) proteins into neatly packed crystalline and non-crystalline domains, aligned along the smooth length of fiber, to create strong, lustrous filaments. [120]
- Wool is made of scaly, crimped, hair-like fibers composed of cross-linked keratin proteins that provide the stretch recovery properties and thermal regulation of wool.
- Fur has some similarities to wool, but fur combines hair fibers with a leather-like skin backing, The hair structure and size depends on the animal and both contribute to unique softness, shine, and warmth.[121]
- Down relies on intricate keratin-like structures with large surface area relative to volume to create highly insulative, lightweight fillers with good compression resistance. [122]

How can innovators capitalize on bottom-up material design? MII is preparing a series of guides on what makes animal-derived materials behave the way they do, in order to equip next-gen innovators with the knowledge to make high quality, sustainable alternatives. The first of the series, "What Makes Silk, Silk?" is available for download at: www.materialinnovation.org/reports. Reports on the remaining material categories are forthcoming. Subscribe to MII's newsletter for the latest updates.

FOLLOW-UP READING AND RESOURCES RELATED TO THIS TOPIC:

Material Innovation Initiative. "What Makes Silk, Silk?"
Available at: https://www.materialinnovation.org/reports

Biomimicry Institute. Resources and initiatives related to nature-inspired technology.
Available at: https://biomimicry.org/

119 B.M. Haines and J.R. Barlow, "The anatomy of leather," Journal of Materials Science 10 (1975): 525-538. https://link.springer.com/article/10.1007/BF00543698
120 Material Innovation Initiative, "What Makes Silk, Silk?" Available at: https://www.materialinnovation.org/reports
121 Sara J. Kadolph and Sara B. Marcketti, "Natural Protein Fibers," Textiles 12th Edition, Pearson Education Inc. (2017)
122 Jing Gao et al., "Structures and Properties of the Goose Down as a Material for Thermal Insulation," Textile Research Journal 77, 8 (2007): 617-626.

7. BIOTECHNOLOGY SCALE-UP

Cellular engineering at scale

In the next-gen materials space, a plethora of materials reliant on biotechnology have emerged. These promising materials are grown from living organisms in a laboratory and designed to replace those derived from animal agriculture. A recent report from the McKinsey Global Institute analyzed the economic and social impact of biological innovation and found that biotech could produce up to 60 percent of the physical inputs to the global economy, ranging from food, health, energy, consumer goods, and materials.[123] However, many of these technologies based on cellular agriculture still have hurdles to overcome before they are commercially available. What will it take to make these "futuristic" next-gen technologies a reality?

Next-gen technologies that rely on biotech approaches include:

- Tissue engineering approaches to make lab-grown leather and exotic skins from cultured animal cells.
- Controlled growth of fungi mycelium for use in next-gen leather.
- Microbial fermentation processes that produce native molecules such as bacterial cellulose, for use in applications such as next-gen leather.
- Precision fermentation processes employing microbe factories to produce proteins or biosynthetic feedstocks for fibers that may find use in any of the next-gen material subcategories. Common applications to date include recombinant spider silk proteins for next-gen silk and recombinant collagen for next-gen leather.

Although reliant on starkly different processes, each of these technologies share a few broad process considerations:

- Organism
- Nutrients
- Growth
- Harvest and conversion
- Scale-up

It is important to note that each of these process considerations are informed by the bottom-up materials design approach of White Space 6. Without a target for material properties and end product performance, the biotech process cannot produce the desired outcome of novel next-gen materials.

We offer a high level overview of each consideration as well as relevant examples for the next-gen materials industry below.

123 Laura Cancherini et al., "What's ahead for biotech: Another wave or low tide?" McKinsey.com, Apr 30, 2021. https://www.mckinsey.com/industries/life-sciences/our-insights/whats-ahead-for-biotech-another-wave-or-low-tide

Organism

The first critical step for each of these biotech approaches is the selection of the production organism. The species of choice is one decision, of course, but the specific strain, or the genetic variant or subtype of that species, is where innovators spend more time.[124] Whether it be the fungal strain used to grow mycelium, the animal cell line used to grow skin tissue, or the bacteria or yeast engineered to produce silk proteins, each process involves the careful selection, optimization, or engineering of the production organism strains. The growth rate of the cells and the ability for the cell to produce the target compound are in part determined by the choice of strain.

When it comes to precision fermentation technologies used for next-gen materials, strain engineering is extremely important, as the process often relies upon altering the DNA of the organism to output specific products, commonly proteins. These proteins are often native to animals but produced by a non-native host in the form of bacteria or yeast cells (i.e., recombinant proteins).

The science behind synthetic protein synthesis is still relatively new. While fermentation of microbes to produce molecules such as alcohol emerged early in history, the ability to engineer organisms to produce bespoke products they didn't evolve to produce is a recent scientific advancement. Recombinant organisms and resultant protein synthesis was first discovered in the 1970s.[125] Genome editing of broad classes of organisms has only recently entered its "revolution" due to the advancements possible with CRISPR Cas9 editing tools, for which the Nobel Prize in Chemistry was awarded in 2020.[126] Many more synthetic biology advancements are white spaces being explored in real time. These advancements will enable faster, more cost-effective approaches that harness biology to create novel materials such as recombinant silk or collagen.

In some instances, organism choice is made through biodiscovery approaches, whereby researchers identify wild strains and bring them back to the laboratory for manufacturing. An example of a next-gen innovator taking this approach is Spora Biotech. Spora Biotech identifies novel strains of fungi from rich ecosystems such as the Amazon and Patagonia, and uses genetic engineering to create proprietary strains. In another example, Nature's Fynd ferments extremophile fungi found in Yellowstone National Park to create food products that may have applications in other sectors.

The selection and engineering of strains is such a priority that entire companies are dedicated to this piece of the puzzle. Ginkgo Bioworks, "the organism company," is a Boston-based company dedicated to building foundries and codebases for biological engineering for therapeutics, food ingredients, and materials. Next-gen innovator Bolt Threads has recently partnered with Ginkgo Bioworks to optimize their recombinant silk protein technology.[127] While currently targeting personal care and cosmetics, this effort may soon translate to next-gen silk fibers for fashion.

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124 Lakna, "What is the Difference Between Strain and Species," PEIAA.com, Apr 1, 2020. https://pediaa.com/what-is-the-difference-between-strain-and-species/

125 Rick Davies et al., "A history of recombinant protein technology in small molecule drug discovery," European Pharmaceutical Review 5, Oct 28, 2014. https://www.europeanpharmaceuticalreview.com/article/27775/history-recombinant-protein-technology-small-molecule-drug-discovery/;
C. H. Taron et al., "Over 40 years in protein expression and purification – a historical perspective," New England BioLabs 3 (2019) https://international.neb.com/tools-and-resources/feature-articles/over-40-years-in-protein-expression-and-purification

126 P.D. Donohoue, "Advances in Industrial Biotechnology Using CRISPR-Cas Systems," Trends in Biotechnology 36, 2 (2018).

127 Ena Cratsenburg, "Bolt Threads Optimizing Silk Protein Production," GinkgoBioworks.com, Aug 5, 2021. https://www.ginkgobioworks.com/2021/08/05/bolt-threads/

Nutrients

Selecting the way to supply and deliver energy to the chosen organism is critical. Without the specific nutrients required for growth, the cells will be unable to produce valuable next-gen materials.

For mycelium leather innovators employing solid-state fermentation, agricultural waste is a common input. Bolt Threads employs sawdust from the wood industry to create their Mylo product.[128] Using waste products offers cost-saving and sustainability benefits. There are currently over a billion tonnes of viable waste worldwide. (See White Space 4.) Researchers have also employed agricultural residues to create custom media for bacterial growth.[129] One drawback is that agricultural waste feedstocks have inherent variability that may pose challenges for ensuring consistent production processes.[130]

One of the biggest challenges for scaling animal-free production of next-gen leather is cell culture media, a cocktail of nutrients including growth factors, amino acids, salts, sugars, and other molecules essential for cell growth and proliferation. For both lab-grown meat and lab-grown leather, cell culture media is one of the biggest cost drivers.[131] Unfortunately, classic mammalian cell culture media relies on fetal bovine serum (FBS), derived from unborn calves. To make a product free from all animal products, innovators in cultured leather (or meat) must develop or use modified media free from FBS. Finding an appropriate replacement for FBS poses additional technical and cost challenges.[132]

Precision fermentation technologies must also fine tune their media to support the microbial culture, with sugars being the classic feedstock. For gas fermentation approaches, employed by PHA innovators such as Mango Materials and Newlight Technologies, the primary feedstocks are carbon-based greenhouse gases.[133] This approach avoids the use of food products or byproducts and may be a more cost effective and sustainable source of nutrients.[134] One challenge for these innovators is to capture these gases as they are emitted from factories, or to extract them directly from the atmosphere in order to produce carbon-negative or carbon-neutral materials.

Optimizing nutrient feedstocks is critical to ensure efficient, effective, and sustainable biotech manufacturing processes.

128 Adele Peters, "This realistic mushroom 'leather' is ready for commercial production," FastCompany.com, Sep 15, 2021. https://www.fastcompany.com/90675864/this-realistic-mushroom-leather-is-ready-for-commercial-production

129 Pratibha Jadhav et al., "Formulation of Cost Effective Alternative Bacterial Culture Media Using Fruit and Vegetables Waste," International Journal of Current Research and Review 10, 2 (Jan 2018): 6-15. https://www.ijcrr.com/uploads/2421_pdf.pdf

130 Pardeep Kumar Sadh et al., "Agro-industrial wastes and their utilization using solid state fermentation: a review," Bioresources and Bioprocessing 5, 1 (Jan 2018). https://bioresourcesbioprocessing.springeropen.com/articles/10.1186/s40643-017-0187-z

131 Liz Specht, Ph.D., "An analysis of culture medium costs and production volumes for cultivated meat," The Good Food Institute, Feb 9, 2020. https://gfi.org/wp-content/uploads/2021/01/clean-meat-production-volume-and-medium-cost.pdf

132 The Good Food Institute, "Deep dive: Cultivated meat cell culture media," gfi.org, accessed Sep 29, 2021. https://gfi.org/science/the-science-of-cultivated-meat/deep-dive-cultivated-meat-cell-culture-media/

133 Diederik van der Hoeven, "Gas fermentation: another promising biobased technology," BioBasedPress.eu, Jul 3, 2016. https://www.biobasedpress.eu/2016/07/gas-fermentation-another-promising-biobased-technology/

134 Peter Dürre, "Gas fermentation – a biotechnological solution for today's challenges," Microbial Biotechnology 10, 1 (2017): 14-16. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5270713/

Growth: equipment and process conditions

Process optimization can be a pain point in biotech manufacturing. To scale processes, the metabolic pathways of the organism must be maximized by keeping the cells "happy." This is typically a combination of strain engineering, nutrient optimization, and specific growth conditions within a bioreactor. In fermentation processes, happy cells lead to higher yields, and higher yields mean more product in a given production run. Optimizing cell densities, contamination mitigation, gas exchange, ingredient concentrations, and environmental controls such as temperature, humidity, light exposure, and pressure are all critical "knobs" in biotech optimization.

Optimizing all these variables can be a daunting task for innovators, reliant on many rounds of experimental trial and error. Scaling from lab scale to full scale production can also mean starting over on a refined process. As such, service providers have emerged with dedicated tools and facilities to accelerate these optimization experiments. For example, Culture Biosciences used cloud-based services to design, monitor, and analyze bioreactors on behalf of customers. Next-gen leather innovator Modern Meadow has used Culture Biosciences small scale, 250 mL reactors as simulated production environments to confirm that desirable strains will perform effectively at scales of 5,000 to 50,000 L tanks.[135]

For tissue engineering applications reliant on cultured animal cells, a supportive scaffold is another critical design factor for both throughput and final properties. Animal cells often require a substrate in order to adhere and proliferate. The choice of materials and structures for this scaffold can dictate the final properties of the tissue construct, and thus also plays a role in process optimization.[136]

Mycelium-based technologies must also consider the role of directed growth on final properties. For example, Mycoworks has patented their Fine Mycelium™ technology process to control the 3D structure of the hyphae filaments within the mycelium as it grows, in order to customize the product for specific applications.[137]

Equipment choices for supporting cell growth are also a critical consideration for next-gen innovators employing cellular agriculture. Bioreactors can vary in size, design, controls, mixing method, and feeding strategy (e.g., batch vs. continuous) all of which must be optimized for type of culture, strain and desired outputs.[138]

135 Culture: The Biomanufacturing Blog, "Scaling up from Culture's 250mL Reactors to 5,000L and 50,000Ll Tanks," Blog. CultureBioSciences.com, Sep 30, 2020. https://blog.culturebiosciences.com/scale-up

136 B.P. Chan and K.W. Leong, "Scaffolding in tissue engineering: general approaches and tissue-specific considerations," European Spine Journal 17, 4 (2008): 467-479. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2587658/#:~:text=Cyto%2D%20and%20tissue%20compatibility%3A%20Scaffolds,culture%20and%20in%20vivo%20implantation.&text=Mechanical%20property%3A%20Scaffolds%20provide%20mechanical,stability%20to%20the%20tissue%20defect.

137 Our Products - MycoWorks, "What is the Fine Mycelium™ process?" MycoWorks.com, accessed Sep 29, 2021. https://www.mycoworks.com/our-products#what-is-the-fine-mycelium-process

138 Tony Allman, "The 4 Different Types of Stirred Tank Bioreactors (STRs)," Infors-HT.com, May 20, 2020. https://www.infors-ht.com/en/blog/the-4-different-types-of-stirred-tank-bioreactors-strs/

Harvest & Conversion: collection, purification, and transformation to final product

Downstream processes and equipment for the collection and purification of the desired product should not be overlooked by biotech innovators. Depending on the strain and process, fermentation methods often involve a separation and purification process to collect the desirable product from the “other stuff” in the soup-like mixture in the bioreactor.[139] When the materials sector competes with pharmaceuticals and food for bioprocessing equipment, supply chain challenges may occur.

For example, during the COVID-19 pandemic, the race for vaccines led to shortages of the filters needed to purify the product from the bioreactors.[140] Innovators must consider complex supply chains, costs, and process optimization for consumables and equipment at the harvest stage.

At the end of the production process, innovators must consider the conversion of the raw output to the final commercial product. For leather grown from animal cells in a laboratory, the use of preexisting tanning processes can be employed. For materials like recombinant silk, the spinning process of the silk is critical to its properties and performance. (See MII’s Silk Report for a deep dive.) Innovators are still working to replicate the complex transformation that occurs inside the gland of animals like silkworms and spiders in order to produce silk of similar quality to the incumbent. Biosynthetics derived from fermentation processes (e.g., PHAs) show promise as drop-in replacements for fossil-based synthetics, but converting PHAs to fibers to replace silk, wool, fur, or down remains a technical challenge. (See White Space 3,5.) For mycelium, each next-gen innovator has employed proprietary approaches for converting the raw, foam-like mycelium into the compacted, flexible sheets of next-gen leather, based on many years of R&D and refinement.

Ensuring that the finished product, whether it be sheets or fibers, can tap into existing handling equipment such as winders/spinners/rollers, and is also compatible with cut and sew operations, is also important.

139 Maribel Rios, “A Decade of Harvesting Methods,” BioProcessIntl.com, Jun 1, 2012. https://bioprocessintl.com/downstream-processing/chromatography/a-decade-of-harvesting-methods-331186/

140 Joe C Mathew, “Not just Serum, shortage of vaccine raw material troubling global vaccine makers,” BusinessToday.In, Mar 10, 2021. https://www.businesstoday.in/latest/economy-politics/story/not-just-serum-shortage-of-vaccine-raw-material-troubling-global-vaccine-makers-290448-2021-03-10

Scale-up

The steps above are critical to the production of biotech-based materials, but commercial success is predicated on the ability to supply large volumes at reasonable costs. A typical journey in biotech company scaling is approximately 10 years and >$100M funding (Figure 9). Scaling a biotech process from bench scale to full production capacity is not a simple process. Many of the technical optimization steps at a bench or pilot production scale will not transfer to large scales, particularly for techniques such as fermentation.

Fundraising trajectory:

A "typical" journey from founding to exit takes about ~10 years that can include >$100M USD in funding

	Pre-Seed	Seed	A	B	C & Above	IPO/ EXITED
Valuation	$0 - $1M	$1M - $15M	$10M - $40M	$30M - $300M+	$100M +	*NA*
Fundraising	$50K - $200K	$500K - $5M	$3M - $20M	$10M – $100M+	$30M – $100M+	*NA*
Revenue	*NA*	*NA*	$0M - 5M	$0M - $10M	$5M - $100M+	*NA*
Typical years to reach stage	0-3 years	0-5 years	3-7 years	5-8 years	6-9 years	> 10 years
Usage of fund	Product market fit validation	Product market fit validation	Product market fit validation	Solving for scalability	Growth and revenue	Growth and revenue
Status with customers	*NA*	Pilot & product optimization	Product launch	Further brand establishment	Expansion into new markets	Strengthening brand image/ market shares
Apparel/ Textiles synbio examples	GALY, Werewool	VitroLabs Inc, Algalife, huue.	Mango Materials, Pili, Colorifix	MycoWorks, Modern Meadow	Spiber, Bolt Threads, LanzaTech	Jeanologia
Ag/ Food synbio examples	Formula, Has Algae, avant	Aranex Biotech, Hakko Bako	Joywell, Motif FoodWorks, mori	Geltor, Memphis Meats, Clara Foods	Perfect Day, Impossible, Apeel Sciences	Ginkgo Bioworks, calyxt

Figure 9. Biotech fundraising trajectory with examples in the textiles industry. Source: The Mills Fabrica, Synbio Playbook for Techstyle startups – A Complete Guide for Founders by Angus Tsang and Jenna Chow. https://www.themillsfabrica.com/platform/reports/

For example, pressure, heat exchange, gas transfer, mixing methods, and other factors will vary substantially between lab scale, pilot scale, and commercial scale fermentation processes. Like many industries, machine learning (ML) and artificial intelligence (AI) are emerging as attractive solutions to rapidly model and iterate bioprocessing conditions towards optimization.[141] There are also challenges in the availability of facilities for at-scale fermentation. According to Warner Advisors, commercial contract manufacturing facilities for fermentation were primarily designed for pharma ingredients, and many of them are currently occupied by preexisting contracts. Innovators entering this space may then be forced to build their own commercial scale facilities or wait for availability by contract facilities.[142] Next-gen innovator Spiber has turned its funding towards building its own in-house manufacturing facility in Thailand and using external facilities in the United States.[143]

The early ages of biotechnology were reserved for high value, low volume products such as therapeutics. However, the recent surge in the use of biotechnology for food applications has allowed low value, high volume products to enter the marketplace. Fermentation products such as Impossible Burger's heme, fungi-based ingredients, and cultivated meat grown from animal cells have parallels to the next-gen materials space. (Read more in Bonus Section.)

141 Vivienne Raper, PhD, "Bioprocessing Warms to Artificial Intelligence," Artificial Intelligence 40, 8 (Aug 2020). https://www.genengnews.com/insights/bioprocessing-warms-to-artificial-intelligence/

142 Mark Warner, "Commercial fermentation: Opportunities and bottlenecks," YouTube.com TheGoodFoodInstitute, May 13, 2021. https://www.youtube.com/watch?v=aqr18eiot9Q

143 Niko McCarty, "Spiber's biomaterials stack: From new production facility to fashion runway," synbiobeta.com, Sep 4, 2019. https://synbiobeta.com/spibers-biomaterials-stack-from-new-production-facility-to-fashion-runway/; Spiber News, "Spiber America LLC receives Iowa economic development incentive package for expansion of production to Clinton, Iowa," Spiber.inc, Nov 20, 2020. https://www.spiber.inc/en/news/detail/id=481

Using cultured animal cells to fabricate next-gen leather or cultivated meat share some of the same scale-up challenges. Finding animal-free nutrients for media, high media costs, capital expenditure on equipment, and process optimization remain challenges for both applications. However, lab-grown leather may have a few scaling advantages over lab-grown meat.

The major benefit of using biotech for materials applications is the lower regulatory risk. Manufacturing products that are intended to enter the human body, such as medicine or food, are rife with safety considerations such as biocompatibility, toxicity, acute or chronic health effects. But materials such as next-gen leather come with far fewer consumer exposure risks and thus fewer regulations. The need for pharma-grade or food-grade equipment may not be necessary, as there is a lower burden for purity. The grown hide will also be processed via tanning for preservation.[144] Similarly, lab-grown leather may have fewer technical challenges than lab-grown meat. Engineering skin is simpler than thick cuts of fat-marbled muscle. In fact, the first commercial tissue engineering product was a skin construct made of human cells developed by Organogenesis and approved by the FDA in 1998.[145]

Figure 10: VTT's process to create continuous sheets of mycelium leather. Source: https://www.intelligentliving.co/continuous-sheets-of-mushroom-leather/

Thin skin constructs don't necessarily require vasculature, which is a huge technical challenge for cultivated meat approaches.[146] The materials and designs for scaffolds or ingredients are also more open-ended for lab-grown leather. In the United States, food products must rely on Generally Recognized As Safe (GRAS) ingredients,[147] whereas next-gen materials can use much broader material suites. In fact, scaffolds can be a part of the bottom-up materials design approach, with the scaffold remaining a part of the composite structure to contribute to mechanical performance. In this way, applying tissue engineering to materials applications such as leather can allow innovators to leapfrog parallel industries such as cultivated meat.

On the mycelium front, scaling is dominated by production capacity of the growth facilities. Mycelium innovators often employ indoor vertical farms, where stacks of trays can grow mycelium sheets over low areal footprints.[148] However, the size of the finished product is then limited by the mold or tray used to grow the mycelium. Innovators at VTT Technical Research center in Finland have developed an approach to create continuous sheets of mycelium leather that may enable larger footprint leather products and more efficient production (Figure 10).[149]

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144 Leather International, "Putrefaction," LeatherMag.com, Nov 15, 2001. https://www.leathermag.com/features/featureputrefaction/

145 Nancy Parenteau, "Skin: The First Tissue-engineered Products," Scientific American 280, 4 (Apr 1999): 83-85. https://www.jstor.org/stable/26058173

146 Andy Tay, PhD, "Scientific Challenges and Solutions for Cultured Meat Manufacturing," GenEngNews.com, Apr 7, 2021. https://www.genengnews.com/tech-exclusives/scientific-challenges-and-solutions-for-cultured-meat-manufacturing/

147 Burdock Group, "Cell-Cultured Meat: Who Will Regulate, FDA or USDA?" BurdockGroup.com, Aug 6, 2018. https://burdockgroup.com/cell-cultured-meat-regulation-fda-usda/

148 Laura Hawkins, "Mushrooms are being transformed into sustainable luxury materials," Wallpaper.com, Jul 25, 2021. https://www.wallpaper.com/fashion/mushrooms-sustainable-fashion-material

149 Luana Steffen, "New Technology Makes Continuous Sheets of Mushroom Leather," IntelligentLiving.co, Jul 11, 2021. https://www.intelligentliving.co/continuous-sheets-of-mushroom-leather/

Fundamentally, many wonder what the future holds for driving down costs in next-gen biotech applications while continuing to increase performance. In the semiconductor industry, a phenomenon known as Moore's law has held true for decades, whereby the number of transistors on a microchip doubles every two years, though the cost of computers is halved, leading to continually more compact and powerful computing at lower costs.[150] Will biotech-based innovations follow this trend? While the complexity of biology has led many to think that Moore's law for biotech cannot exist, certain breakthroughs such as genome sequencing have outpaced Moore's law (see the Carlson curve).[151] With the sufficient allocation of brainpower and resources, the "golden age" of biotech could enable innovators to break through scale-up challenges to price parity.

Because of the unique challenges faced by biotech innovators, a number of accelerators and incubators have emerged for startups in this space. Examples in the United States include Bay-area Indiebio and Berkeley Biolabs, as well as the newly launched Nucleate program in the Boston area.

Clearly there are many pain points in a biotech process that need to be de-risked in order for the process to be successful. However, the promise that these technologies may enable in the development of sustainable, high-performance, animal-free materials is palpable. New-to-the-world science comes with challenges, including staffing with a skilled workforce with experience in materials applications. Investors, innovators, brands, and the media need to work together to understand that these white spaces require significant efforts, collaboration, investment, and most importantly, patience, to be successful.

FOLLOW-UP READING AND RESOURCES RELATED TO THIS TOPIC:

The Mills Fabrica. Reports: Synthetic Biology: Opportunities in Fashion and Food, and SynBio Playbook for Texstyle Startups.
Available at: https://www.themillsfabrica.com/platform/reports

Biofabricate and Fashion for Good. Understanding "Bio" Material Innovations.
Available at: https://fashionforgood.com/news/resource-library/

150 Carla Tardi, "Moore's Law," Investopedia.com, Feb 23, 2021. https://www.investopedia.com/terms/m/mooreslaw.asp

151 Marshall Honorof, "Biotech's Explosive Evolution Outpaces Moore's Law," NBCNews.com, May 13, 2013. https://www.nbcnews.com/id/wbna51870335;
Patrick Boyle, "Microbes and Manufacturing: Moore's Law Meets Biology," The Bridge, National Academy of Engineering 49, 4 (Dec 2019). https://www.nae.edu/221231/Microbes-and-Manufacturing-Moores-Law-Meets-Biology

CONCLUSION

"Like any blank canvas, white space can provoke fear and hesitation."[152] But taking on these challenges will enable the next-gen materials industry to deliver on performance and aesthetic and to protect our planet and its inhabitants. We have identified these 7 white spaces on behalf of researchers, suppliers, brands, innovators, and investors to clarify where industry-wide efforts should best be concentrated. There will be no silver bullet to solve every problem. We encourage the ecosystem to work together to understand these issues and fill these white spaces with transformative innovation.

> "*We cannot solve our problems with the same level of thinking that created them.*"
>
> *Albert Einstein*

152 Idris Mootee, "White Space Mapping – Seeing the Future Beyond the Core," InnovationManagement.se, Jun 13, 2013. https://innovationmanagement.se/2013/06/13/white-space-mapping-seeing-the-future-beyond-the-core/

BONUS SECTION: LEARNINGS FROM THE ALTERNATIVE PROTEINS INDUSTRY

This section is provided by [The Mills Fabrica], a go-to solutions platform for sustainability in food and fashion. In this section, we take lessons from the alternative-protein space and apply them to next-gen materials.

Introduction

Using animals for food and fashion share similarities across the value chain. Both rely on a great deal of land, water, and other resources for production, causing significant environmental impact.

Innovation in “alternative proteins” has exploded in recent years. Alternative protein refers to protein that does not come from animals, such as plant-based and cultivated meat. However, this animal-free concept is equally applicable to fashion, with next-gen materials able to provide humane, sustainable alternatives to animal-derived leather, wool, fur, silk, down and exotic skins.

Source: Impossible Foods.

Source: Vegan Fashion Week Feb 2019 in Los Angeles. Mateja Benedetti by McKinsey Jordan.

Many consider Beyond Meat (founded in 2009) and Impossible Foods (2011) to be the breakthrough players in the rise of alternative proteins. They did not make another veggie burger that was “good enough” for people who were already vegetarian. Rather, they sought to “biomimic” animal meat’s structure to produce plant-based meat intended for meat-eaters.

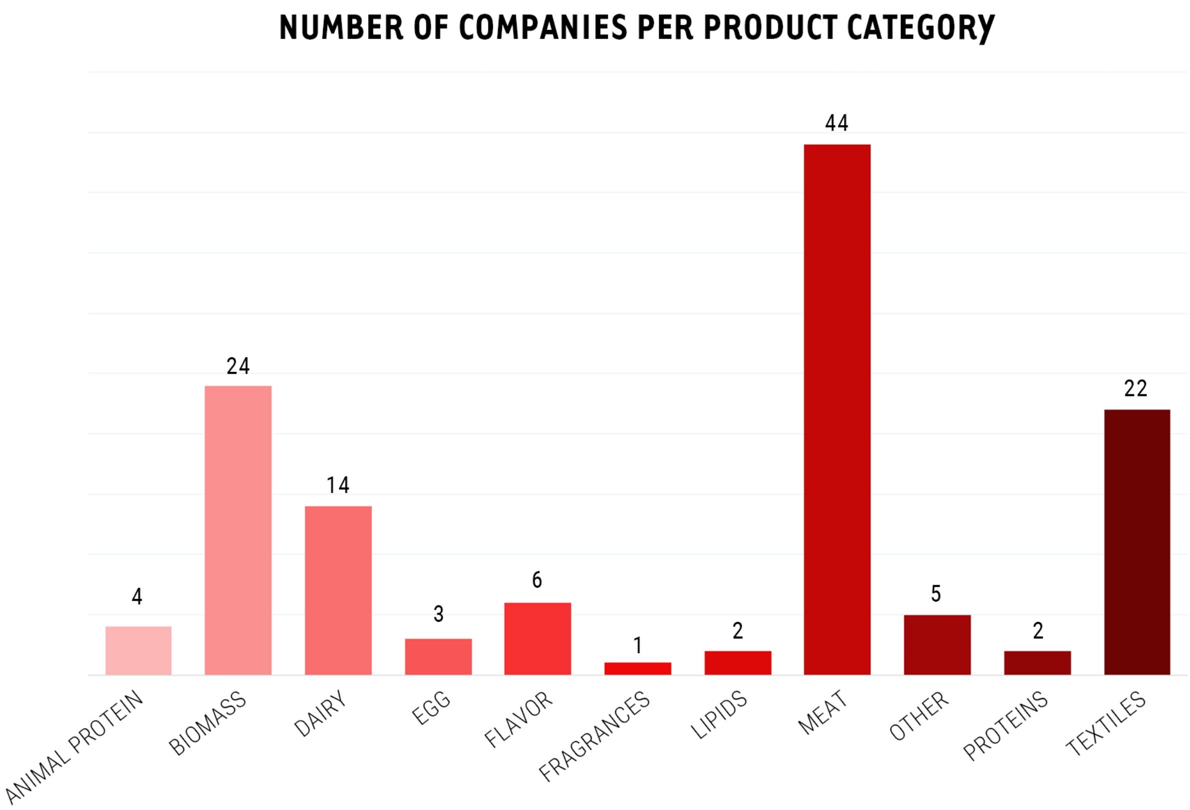
This led to a torrent of new startups seeking to use various technologies to create animal-free meat, eggs, and dairy. In addition to using plants, these startups are using mycelium, precision fermentation, and cultured animal cells.

As we will see below, a similar path is being followed in the materials space. Although starting some years after alternative proteins, the development of next-gen materials has several advantages. For example, the industry can leverage technological and production advances pioneered by the alternative protein field. Furthermore, people do not have the same attachment to cow leather or silkworm silk as they do to cow steak or swine bacon. This makes it easier to market next-gen materials to most consumers.

Using the Same Technologies Across Food and Fashion

The similarity between food and fashion can be seen in the technologies used. "Cellular agriculture" is a relevant term here. It was coined by New Harvest in 2015, and generally means farming cells rather than whole plants or animals. Cellular agriculture is sometimes used as shorthand for making animal products without animals, but it can also include farming fungi or plants for products you would normally expect to come from some type of farm. In terms of the number of companies, cultivated meat currently is the most popular category in cellular agriculture, followed by biomass and then textiles.[153]

Exhibit 1: Number of Cellular Agriculture Companies per Product Category



Source: Cellular agriculture landscape by Nate Crosser. https://ecotech.substack.com/p/cellular-agriculture-landscape

As discussed below, the same technologies used to produce animal-free food can be applied to the fashion industry. For instance, using mycelium, Ecovative Design is producing animal-free leather as well as providing structural components for plant-based and cultivated meat. However, as seen in Exhibit 2, most startups are dedicated to either the food or fashion space. Since the underlying technologies can work for both food and fiber, it may be possible to leverage economies of scale across industries, driving down production costs.

153 Nate Crosser, "Cellular agriculture: definition, products, industry landscape, & white space," Fifth Industrial, EcotechSubstack.com, Apr 13, 2021. https://ecotech.substack.com/p/cellular-agriculture-landscape

Exhibit 2: Alternative Protein Startups in Food and Fashion by Technology

Technology	Food	Fashion
Precision Fermentation	Clara Foods, Impossible, remilk., Perfect Day, BioscienZ, CHANGE, GELTOR, New Culture, PROVENANCE, nourish INGREDIENTS, real vegan cheese, novacca, Imagindairy	BOLT THREADS, Spintex, Spiber, Modern Meadow, AMSilk
Tissue Engineering	TurtleTree Labs, BIOMILQ, mosa meat, JUST, UPSIDE Foods, MEMPHIS MEATS, Hs Higher Steaks, MISSION BARNS, ALEPH FARMS, FUTURE MEAT, SuperMeat, Meatable, BlueNalu, Shiok Meats	PROVENANCE, VitroLabs Inc, QORIUM LEATHER
Mycelial Growth	prime roots, meati, My Eats, ECOVATIVE DESIGN	ECOVATIVE DESIGN, BOLT THREADS, MYCOWORKS, MYCL Mycotech Lab, MYLIUM, mogu

Source: The Mills Fabrica
Note: This table is not exhaustive and for illustrative purposes only.

The primary technologies currently in use are:

Precision fermentation uses microbial hosts as factories to produce target compounds.

Traditionally, fermentation is used in the production of alcoholic beverages and fermented foods such as yogurt. With the help of recent advances in gene editing, fermentation is now capable of producing a wider range of new materials, including proteins, biopolymers, and chemical precursors. This advanced fermentation technique is referred to as precision fermentation. Host microbes are first genetically modified using recombinant DNA technology such as CRISPR-Cas9. These genetically edited microbes are then used as "factories" to produce desired molecules through fermentation. This process is most commonly used to produce insulin and rennet, a protein used in cheese production. Precision fermentation is currently used to produce animal-free protein alternatives, such as dairy protein (Perfect Day), egg proteins (Clara Foods), and gelatin (Geltor). Similarly, this same technique can be applied to the fashion industry to create protein-based fibers, such as synthetic spider silk (Spiber, Bolt Threads).

Tissue engineering was first developed for biomedical applications with the purpose to repair and regenerate human tissues and organs.

This cell-based technology makes it possible to grow in-vitro tissue, and this subsequently inspired the development of cultivated meat such as seafood (BlueNalu), chicken (Future Meat), beef (Aleph Farms). This process starts by taking a biopsy containing stem cells from an animal, after which the cells are placed in a culture media that provides the nutrients needed for the cells to multiply. Under a suitable environment, the cells will then differentiate into muscle, fat, and connective tissues, growing on a scaffold into the desired type of meat. This same technology can be applied to the making of animal-free materials such as leather (VitroLabs) for the fashion industry. Seeing how transferable the technology is across sectors, we are expecting to see more animal-free materials – such as fur, wool, and down – in the future.

Mycelial growth has a long history.

As well as being used for food and precision fermentation, fungi can be used to directly create new materials. Mycelium, also known as the root of the mushroom, has a unique, fibrous structure with great insulating and moisture-absorbing properties.[154] This makes it an excellent alternative to single-use plastic packaging materials. Today, mycelium is used in both the fashion and food industries, creating alternatives that closely mimic the characteristics of both meat (Meati) and leather (Bolt Threads, Mycoworks).

154 NEFFA: Growing the Future of Fashion, "Mycelium textile," neffa.nl, accessed Sep 10, 2021. https://neffa.nl/portfolio/mycelium-textile/

Challenges: Bolstering Performance and Lowering Costs

Stepping up the performance of animal-free fashion is a key to driving further adoption. When next-gen materials provide the qualities consumers expect, the barrier to entry becomes that much lower. We can see examples of this in the food space:

- Both Beyond Meat and Impossible Foods use coconut oil to replicate the mouth-coating experience of animal fat;
- In order to mimic the red color of beef, Beyond Meat uses beet extracts;[155]
- Perfect Day uses precision fermentation to produce milk with the same taste and cooking performance as cow's milk.[156]

Production costs need to go down as well. Beyond Meat's founder and CEO Ethan Brown believed that plant-based meat will cost less than meat in several years.[157] Cultivated meat startup Future Meat Technologies achieved a milestone by reducing the production cost of a cultured chicken breast to $7.50.[158]

The significant progress in cost-cutting in both plant-based and cultivated meat has been paralleled with progress in precision fermentation (Exhibit 3). All this provides reasons to believe that as these technologies continue to mature and production scales up, next-gen materials will also continue to drop in price.

Exhibit 3: Cost Reductions Milestones by Alternative Protein Companies

Alternative Protein Company	Announcements	Announcement Date
Aleph Farms	Aleph Farms' beef patty has gone down to $100 per pound in early 2019.	Apr 2019
Memphis Meats	The price of Memphis Meat has dropped from $9000 per pound to below $1000 per pound in a year.	Jun 2020
Eat Just	Mung-bean-based Just Egg has dropped from $7.99 to $5.99 in March 2020 and then down to $3.99 in January 2021.	Jan 2021
Future Meat Technologies	Future Meat Technologies has reduced the production cost of a cultured chicken breast to $7.50.	Feb 2021
Impossible Foods	Impossible Foods is cutting down its prices by 20% at US grocery stores. Retail prices are expected to drop to $5.49.	Feb 2021
Beyond Meat	A pound of ground Beyond Meat has grown down to $5.70.	Jun 2021

Source: The Mills Fabrica; https://civileats.com/2020/07/08/inside-the-race-for-lab-grown-meat/

155 J. Kenji López-Alt, "How Do They Make Plant-Based Meat Behave Like Beef?" NYTimes.com, Mar 3, 2020. https://www.nytimes.com/2020/03/03/dining/plant-based-meat-science.html

156 Rebecca Cairns, "This startup is creating 'real' dairy, without cows," edition.cnn.com, Aug 12, 2021. https://edition.cnn.com/2021/08/12/business/perfect-day-dairy-protein-hnk-intl-spc/index.html

157 Rina Raphael, "Exclusive: Inside Beyond Meat's innovative future food lab," FastCompany.com, Jul 19, 2018. https://www.fastcompany.com/90202590/exclusive-inside-beyond-meats-innovative-future-food-lab

158 Future Meat Technologies, "Future Meat Technologies Reduces Cost of Cultured Chicken Breast Below $10," PRNewswire.com, Feb 1, 2021. https://www.prnewswire.com/news-releases/future-meat-technologies-reduces-cost-of-cultured-chicken-breast-below-10-301218910.html

Creating Consumer Demand

An increasing awareness of alternative protein could likely accelerate the growth of animal-free fashion in the near term. In this sense, it is promising that plant-based and cultivated meat regularly make headlines and are relatively visible. From restaurants serving plant-based nuggets to stacks of plant-based burgers on supermarkets' shelves, the general public, whether they have consumed such products before, are increasingly familiar with animal-free meat.

However, this did not happen overnight. In part, creating consumer demand requires a well-crafted distribution strategy. For example, when Impossible Foods started, they first sold at premium restaurants before selling at Burger King.

In that sense, the trend in fashion resembles what happened in food previously. For example, this year, startup MycoWorks partnered with high-end retailer Hermès to produce the latter's classic travel bag from mycelium instead of cow leather.[159]

Famous fashion brands adopting animal-free materials can create consumer awareness. To enable scale-up of the materials however, there will need to be actual mainstream purchases. This will require lower prices than commanded by exclusive retailers.

Regulatory Barriers

Food regulations can take years to develop and different countries and/or regions are likely to be adopting new, novel foods such as alternative proteins at very different pace (Exhibit 4). In comparison, the fashion industry should be less prone to regulatory control as the food industry. There is less public and regulatory concern over products made by next-gen materials. This is another factor favouring the acceleration of the next-gen industry.

Exhibit 4: Regulations on Alternative Protein by Country

Country	Regulations	Announcement Date
	Cultured meats that are not genetically modified will be regulated under European Food Safety Authority (EFSA)'s Novel Foods Regulation. The EFSA will perform a risk assessment on the product before it comes to the market.	Nov 2015
	The Food and Drug Administration (FDA) and the United States Department of Agriculture (USDA) agreed that the FDA will oversee the pre-market safety consultation process by evaluating the production process as well as the biological material produced, and the USDA will inspect the subsequent processing and labelling process.	Mar 2019
	The Ministry of Agriculture, Forestry and Fisheries (MAFF) established a study group to investigate alternative and cultured meat with an aim to diversify protein sources in the Japanese diet.	Apr 2020
	It was brought up during the National People's Congress that cultured meats can be categorized as novel food and regulated under China's legislation for Novel Foods (新食品原料安全性审查管理办法), and prioritize the evaluation of food safety and production process, similar to that of EU and the US.	May 2020
	Singapore Food Agency (SFA) required novel food companies to undergo a pre-market assessment to ensure the safety of their novel food products before launch. SFA also established the Novel Food Safety Expert Working Group to provide scientific advice on the process. SFA approved Eat Just to sell its cultured chicken meats.	Nov 2020

Source: The Mills Fabrica

159 Rachel Cormack, "Why Hermès, Famed for Its Leather, Is Rolling Out a Travel Bag Made From Mushrooms," RobbReport.com, Mar 15, 2021. https://robbreport.com/style/accessories/hermes-vegan-mushroom-leather-1234601607/

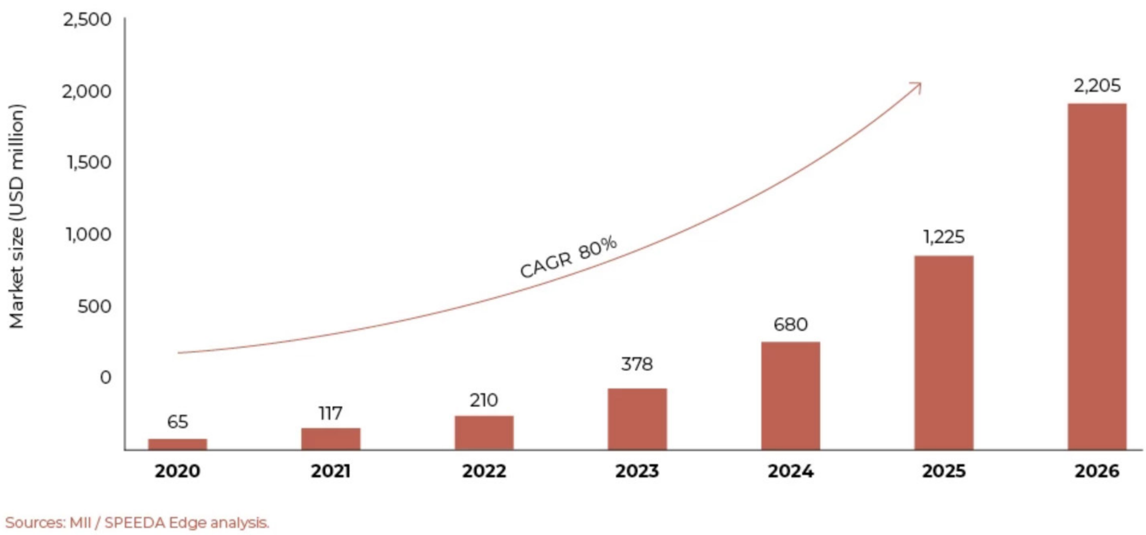
Looking Ahead

To conclude, there are similarities across food and fashion when it comes to the adoption of animal-free products. From a technology perspective, food and fashion share similar technologies and similar challenges. Brand involvement will be an important driver of adoption in the short term. In the long term, improved performance and lower costs will allow animal-free food and fashion to be just another everyday shopping category appreciated by the general public.

According to the Boston Consulting Group, alternative protein represented only 2% of the protein market in 2020. But they expect that by 2035, with additional clarity from regulators and advances in technology, 22% of all the meat, seafood, eggs, and dairy eaten around the globe is likely to be from non-animal sources. Given similarities with alternative protein, we can expect a similar trajectory for next-gen materials.

Based on all of these factors, the Material Innovation Initiative estimates that sales of next-gen direct replacements for conventional animal-based leather, silk, down, fur, wool, and exotic skins, could be expected to grow 80% annually over the next 5 years (Exhibit 5).

Exhibit 5: Projection of Growth of the Next-gen Materials Global Wholesale Market



Source: State of the Industry Report: Next-Gen Materials, Material Innovation Initiative. https://www.materialinnovation.org/state-of-the-industry

160 Ben Morach et al., "Food for Thought: The Protein Transformation," BCG.com, Mar 24, 2021. https://www.bcg.com/publications/2021/the-benefits-of-plant-based-meats

ABOUT MATERIAL INNOVATION INITIATIVE

At MII, we envision a world where the materials we interact with everyday, from our shoes to our car seats, are produced in a way that allows animals, the planet, and future generations to thrive. We aren't the only ones. Consumers and companies alike are searching for sustainable solutions that are functional, fashionable, and cost-effective, but today's options are few and far between.

Markets and technology have the power to drive deep industry change, from raw material selection to the runway. When next-gen materials can compete with the outmoded and polluting materials of today on price and performance, we will see a dramatic shift in the status quo toward a more sustainable future. In this future, the sustainable option will be the default option.

ABOUT THE MILLS FABRICA

Fabrica is the innovation arm of The Mills – dedicated to creating techstyle startup success stories and building a global techstyle community. We are an open platform for innovation, facilitating collaboration between startups, brands, retailers, manufacturers, academic and research institutions and more.

We run a cross-border incubation programme both in Hong Kong and the UK, bridging the east and the west to support techstyle startups through exposure, connections and advisory. This provides startups access to our global network no matter where they are in the world. We also have an investment fund that supports and invests in techstyle globally.