UNDERSTANDING "BIO" MATERIAL INNOVATIONS:

a primer for the fashion industry

Front Cover Image:
MOON PARKA by The North Face Japan (GOLDWIN Inc.) & Spiber
SEM bacteria image: David Gregory and Debbie Marshall

UNDERSTANDING "BIO" MATERIAL INNOVATIONS:

a primer for the fashion industry

BIOFABRICATE

FASHION FOR GOOD

ACKNOWLEDGMENTS

We would like to extend our thanks to the dozens of innovators, brands, manufacturers and industry stakeholders who have helped us to develop this report – their patient input has allowed us to dive into and explore the topic of biofabrication and the broader field of biomaterials and substantiate our findings with detailed insights. Our hope is that this will further enhance innovation partnerships between different stakeholders in this space and drive forward the adoption of solutions.

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DISCLAIMER

This report has been produced by a joint team from Biofabricate and Fashion for Good. The authors take full responsibility for the contents and conclusions. The participation of the industry experts and affiliates who were consulted and acknowledged here, does not necessarily imply endorsement of the report's contents or conclusions.

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ABOUT

BIOFABRICATE

Biofabricate's vision is 'A sustainable material world. Built with biology, not oil'. Our unique NYC based team brings insights and expertise that only come from having worked both within biotech startups and the design industries.

We drive sustainable biomaterial innovation for all sectors through our global network of startups, brands, and investors. We do this in multiple ways. Providing strategic consulting services helping you understand and navigate the emerging field of 'bio' materials. We deliver tailored talks and workshops. We craft brand strategy and creative direction. We are experts in design and biomaterial product prototyping. We produce design-led events in both NYC and London that convene the industry to explore, connect and showcase the latest products. And we author expert reports, diligence technologies, and produce resources to deepen interactions.

Suzanne Lee is CEO and founder of Biofabricate. A biomaterial pioneer, growing microbial materials for fashion since 2003, she coined the term 'Biocouture™'. Between 2014 and 2019 she was Chief Creative Officer of Modern Meadow. Suzanne is the author of 'Fashioning the Future: tomorrow's wardrobe', advisor to 'Parley For The Oceans' on biomaterials, a TED Senior Fellow, and Launch Material Innovator - an initiative of NASA, Nike, USAID and the US State Department.

Dr. Amy Congdon, Head of Design Intelligence at Biofabricate, is a designer with over 10 years of experience in the field of biofabrication. She was previously Associate Director of Materials Design at Modern Meadow. Her PhD in 'Tissue Engineered Textiles' was conducted in collaboration with Central Saint Martins and Kings College (in the Biomaterials, Biomimetics & Biophotonics division at Guys Hospital London).

FASHION FOR GOOD

Fashion for Good is the global initiative that is here to make all fashion good. It's a global platform for innovation, made possible through collaboration and community. With an open invitation to the entire apparel industry, Fashion for Good convenes brands, retailers, suppliers, non profit organisations, innovators and funders united in their shared ambition.

At the core of Fashion for Good is our Innovation Platform. Based in the Amsterdam headquarters and recently expanding the programme to South Asia, the global Fashion for Good accelerator programme gives promising startup innovators the expertise and access to funding they need in order to grow. Our scaling programme and our foundational projects support innovations that have passed the proof of concept phase, initiating pilot projects with partner organisations and guided by our dedicated team that offers bespoke support and access to expertise, customers and capital. Our Good Fashion Fund catalyses access to finance to shift at scale to more sustainable production methods.

Fashion for Good also acts as a Convener for Change, with the world's first interactive museum dedicated to sustainable fashion and innovation. In our headquarters, Fashion for Good houses a Circular Apparel Community coworking space, creates open source resources like its Good Fashion Guide that provides practical advice to implement cradle to cradle™ certified apparel as well as white papers and reports investigating industry practices and developments.

Fashion for Good's programmes are supported by founding partner Laudes Foundation (formerly C&A Foundation), cofounder William McDonough and corporate partners adidas, C&A, CHANEL, BESTSELLER, Galeries Lafayette Group, Kering, Otto Group, PVH Corp., Stella McCartney, Target and Zalando and affiliate partners Archroma, Arvind, Birla Cellulose, HSBC, Norrøna, vivobarefoot and Welspun.

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EXECUTIVE SUMMARY

The last 5 years have seen a pronounced increase in excitement around "biomaterials" for the fashion industry. As brands consider their environmental and social impacts, along with rising ethical concerns from consumers, the search for more 'sustainable' alternatives is driving innovation. Wider trends are further contributing to interest in biomaterials; from climate change and the potential for lower carbon footprints vs fossil based synthetic materials, the war on plastics, to the rapid growth of veganism[1] and a rush to find alternatives to animal derived materials. Biomaterials, however, remain an ill defined category.

What exactly are biomaterials? If asked, most people will stumble to share an understanding of what precisely a biomaterial is. And what are biofabricated, biosynthetic, or biobased materials? Are they all pretty much the same thing? Are they all sustainable? Are they all biodegradable or compostable? Are they "natural"?, "vegan"?, "clean"?, "healthy"?, "non toxic"? - and what do we even mean by those terms? These, and other questions, represent a widespread ignorance in relation to biomaterials not just on the part of consumers, but by fashion brands and even some material innovators themselves.

Without understanding the nuances of 'bio' terminology it is not possible to answer any of the above questions. It is not safe to assume that "bio is better" or that "bio means biodegradable". It is also not possible to directly compare different biomaterials with each other.

In the absence of an existing guide to biomaterials, and specifically the most recent innovations: biofabricated materials, which harness living organisms in their production, this report draws on insights from expert industry insiders to both clarify definitions and share insights for the benefit of brands and innovators alike. Through interviews and surveys with over 30 material innovators and consumer brands, we have synthesized learnings laying a foundation for the fashion industry to understand 'bio' innovations.

Here, we provide a set of biomaterial definitions representing key material technologies being practiced today. We present a model to better understand those different biomaterial technologies as well as a series of high level process diagrams highlighting key steps in material production including potential inputs and outputs to help identify impacts hotspots.

WHAT'S IN A NAME?

We start with definitions. Terms that may be used by material innovators include biobased, biosynthetic and biofabricated. With the exception of biobased, other 'bio' prefix terms lack broadly agreed upon definitions. To assist brands, innovators and other stakeholders in a shared understanding of different biomaterial technologies and their potential impacts, there is a need for a standardized language.

Image: Microsilk™, Bolt Threads

HERE, WE PROVIDE A SET OF BIOMATERIAL DEFINITIONS REPRESENTING KEY MATERIAL TECHNOLOGIES BEING PRACTICED TODAY. **WE PRESENT A MODEL TO BETTER UNDERSTAND THOSE DIFFERENT BIOMATERIAL TECHNOLOGIES** AS WELL AS A SERIES OF HIGH LEVEL PROCESS DIAGRAMS HIGHLIGHTING KEY STEPS IN MATERIAL PRODUCTION INCLUDING POTENTIAL INPUTS AND OUTPUTS TO HELP IDENTIFY IMPACTS HOTSPOTS.

Exploring the origins of how certain terminology has been co opted and adapted from the field of biomedical research, we discuss what makes sense for the fashion industry, and acknowledge that these terms will likely continue to evolve. Having reviewed existing resources, through consultation and our own synthesis, we arrive at distinct biomaterial definitions for today.

Figure 1 provides a set of biomaterial terms representing key material technologies being practiced today. It also includes example materials:

Biobased materials include everything from conventional as well as non animal "leathers" that contain fruit or vegetable waste combined with synthetic polymers, through to a pure cotton fabric or indeed a polyester cotton mix.

Biofabricated ingredients only include microbially produced building blocks for both "natural" and "synthetic" polymers; such as, respectively, silk and nylon.

Biosynthetic materials include the production of chemicals for "synthetic" polymers, such as precursors for nylon and polyester, obtained via catalytic conversion of biomass or biofabricated using living microbes in fermentation processes

Bioassembled materials include 'leathers' grown by mycelium, bacteria or mammalian cells.

Figure 2 shows our model for understanding different biomaterial technologies. Here's how we view the relationships between different terms and technologies:

- Everything falls under the all encompassing, but least specific term; 'biomaterial'.
- All biomaterials are biobased (but the bio content can vary radically from less than 10% to 100%).
- Most biosynthetic, biofabricated, or bioassembled materials can also be described as biobased.
- Some biosynthetic materials are biobased, but not biofabricated.
- Some biosynthetic materials contain biofabricated ingredients which use living organisms in their production.
- All biofabricated materials use living organisms (microbes, rather than plants or animals) in their production.
- All biofabricated ingredients use living organisms to produce building blocks that need further processing in order to make a macroscale material structure
- All bioassembled materials use the living organism to grow into the actual macro material structure.

Critically, the name attached to any material doesn't change how it has been made, its impacts, or its end of use. This is why bio terms applied to a product shouldn't only be taken at face value. It is essential to go a level deeper in order to understand each specific material's process.

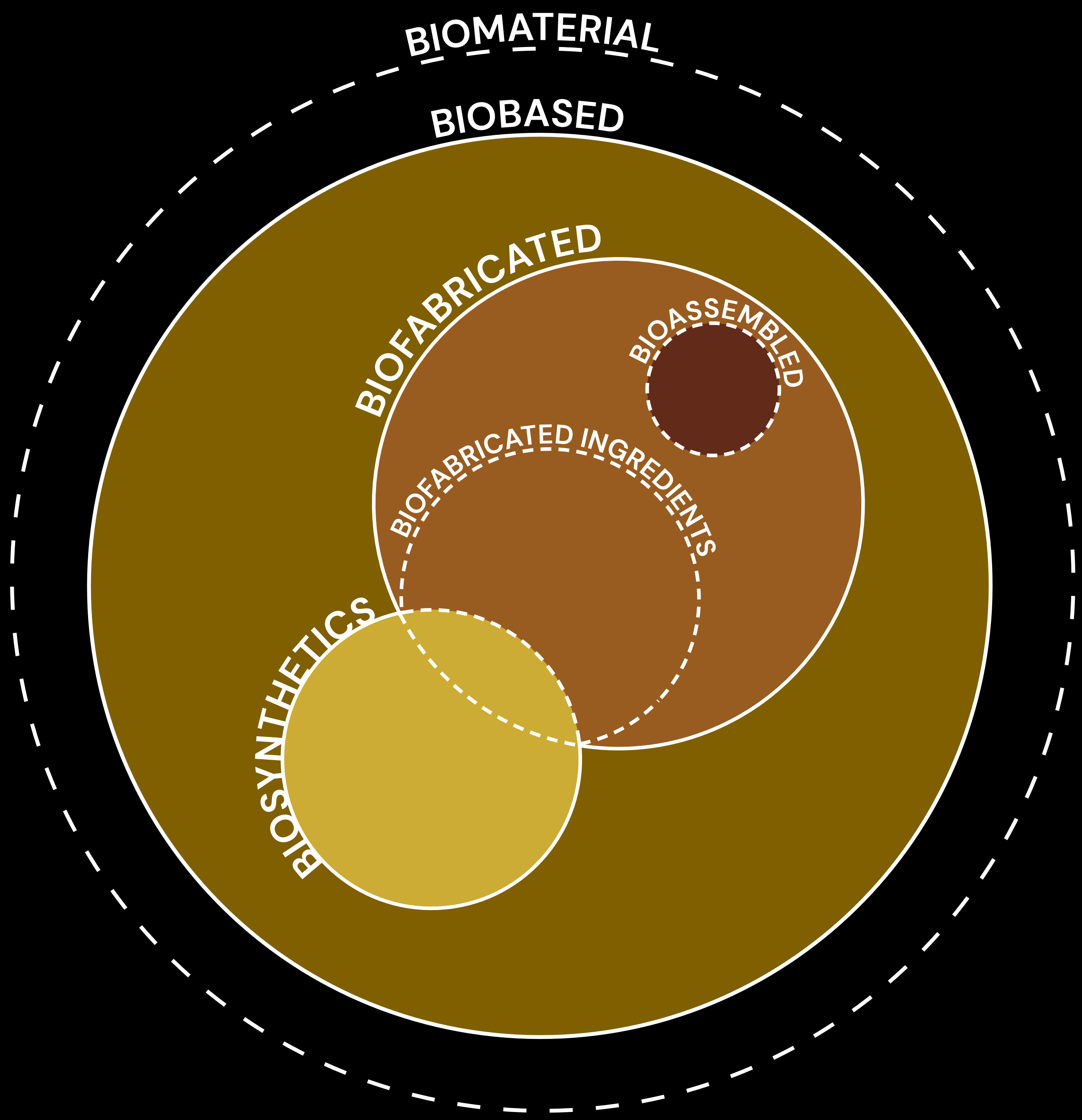

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Figure 1: 'Understanding 'Bio' Material Technologies'

DEFINING "BIO"

BIOMATERIAL

'Biomaterial' is a term used to indicate materials that have non-specific biological association.

Examples of biomaterials could be any of the materials listed in this table.

BIOBASED

Biobased materials are 'wholly or partly derived from biomass, such as plants, trees or animals (the biomass can have undergone physical, chemical or biological treatment)'*. (excluding those derived from fossil sources)

Examples of biobased materials would include, but are not limited to: natural fibers (e.g. cotton, wool and silk), manmade cellulosics (e.g. viscose), natural polymers (e.g. chitin, keratin and casein), animal leathers and their alternatives, through to polycotton blends (where the biocontent meets the minimum stipulated requirement).

BIOFABRICATED MATERIALS

Biofabricated materials are produced by living cells (e.g. mammalian) and microorganisms such as bacteria, yeast and mycelium.

Examples of biofabricated materials would include fermented biosynthetic & biofabricated ingredients and bioassembled materials as below.

BIOSYNTHETIC

Biosynthetics are synthetic polymer materials comprised, in whole or in part, of bio-derived compounds. These compounds can either be made with an *input* of biological origin (biomass), and/or where the *process* is performed by a living microorganism.

Examples of biosynthetics would include the fermentation (of sugars, GHGs etc.) or the catalytic conversion of biomass to create precursor chemicals for synthetic polymers such as nylons, polyesters and polyurethanes.

BIOFABRICATED INGREDIENTS

Biofabricated ingredients are building blocks produced by living living cells and microorganisms e.g. complex proteins like silk or collagen. They need further mechanical or chemical processing in order to make a macroscale material structure.

Examples would include fermented recombinant silk which then has to be spun into a fiber, or processed to form a sheet material.

BIOASSEMBLED

A bioassembled material is a macroscale structure that has been grown directly by living microorganisms such as mycelium or bacteria.

Examples would include mycelium or microbial cellulose leather alternatives.

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Figure 2: 'Defining Bio'

*European Committee for Standardization, 'Biobased products' [online] Dec'20

NOT ALL BIOMATERIALS ARE THE SAME

The word "biomaterial" masks differing technology approaches, inputs and impacts. A key takeaway is that blanket assumptions or statements cannot be made about any biomaterial. Each biomaterial must be considered on a case by case basis regarding its manufacturing process, function and impact. If a material is described as "clean" - by what standard? If "sustainable" - what metrics are being used? If "better" - compared to what? How do we understand the difference between say, a "mushroom leather" and a "fruit leather" or compare a synthetic with a biosynthetic?

Following the definitions, we dive deeper to explore examples of various technological processes represented with a series of high level diagrams. **Figure 3** is an archetype of the system we have created which enables further extrapolations. We break down the key processes in the manufacturing steps of various biomaterial technologies and their potential inputs and outputs. They reveal different technologies and help identify impacts hotspots allowing for side by side biomaterial comparisons.

Each principal biomaterial category is illustrated by one or more such examples. Importantly, they are not intended to represent any one company or be exhaustive, but rather to be indicative; a starting point for understanding the many nuances of different biomaterial processes. Collectively, we hope the diagrams constitute a useful tool for any new material innovator wanting to check their unique value proposition and any fashion brand looking to better understand processes and potential impacts for relative biomaterials.

A FOCUS ON DEVELOPING BIOFABRICATED MATERIALS

Having laid the foundations for differentiating biomaterial production, we then examine more closely the unique challenges of developing and scaling "biofabricated" materials in particular. Using the learnings from innovators across all stages of market readiness, from seed to build out of international commercial plants, we provide a qualitative analysis of the roadmap to scale.

We unpack the difference between lab, bench, pilot and commercial scale - and how ideas of scale do not mean the same thing to everyone. We note that many new biomaterials, regardless of their origin and production, will go through further processing or perhaps be blended with other materials, and that these stages may require startups to partner strategically to help with that technical development. We cover when and how to partner in this space, and what makes for successful relationships.

Alongside this, we outline an LCA and sustainability guide for startups and brands to use during the innovation process. This maps what startups may consider doing as they move through different technology readiness levels, as well as identifying what brands are looking for at each stage. We also include key learnings and questions brands can ask stakeholders throughout their supply chain as well as tools to assist innovators in conversation with their partners. The diagrams help identify impact hotspots for lifecycle assessments. We encourage brands to think carefully about what they actually need in terms of impact information and when and how they can best support innovators on their developmental journeys.

Image: PURA materials, by Mogu

KEY LEARNINGS FOR BRANDS & INNOVATORS

From speaking with both innovators and brands, a principal learning is that the foundation for success is built on strong partnerships. There are tangible actions both brands and innovators can take in this regard.

For Brands:

- Clearly articulate your goals for a new material
- Identify when, where and how you can contribute expertise
- Be realistic about how long you are willing to wait for a material
- Jointly agree on achievable project milestones, deliverables and timelines
- Contribute a clear sustainability viewpoint
- Share which impact hotspots are a priority, provide data or targets where possible
- Be frank about price and material performance in the short, medium and long term

Having a continuity of relationship management helps both parties on often long development journeys and supports innovators who can struggle when project ownership isn't clear within large organizations. Most importantly, brands must recognize it is not possible to draw comparisons between materials in development to those that have been fully optimized at global scale for many decades.

For Innovators:

- Be transparent and honest regarding development timelines
- Clearly communicate key challenges
- Set expectations from the start and articulate where choices or compromises may occur
- Leverage a brand partner's competencies where appropriate to move faster

EXAMPLE DIAGRAM

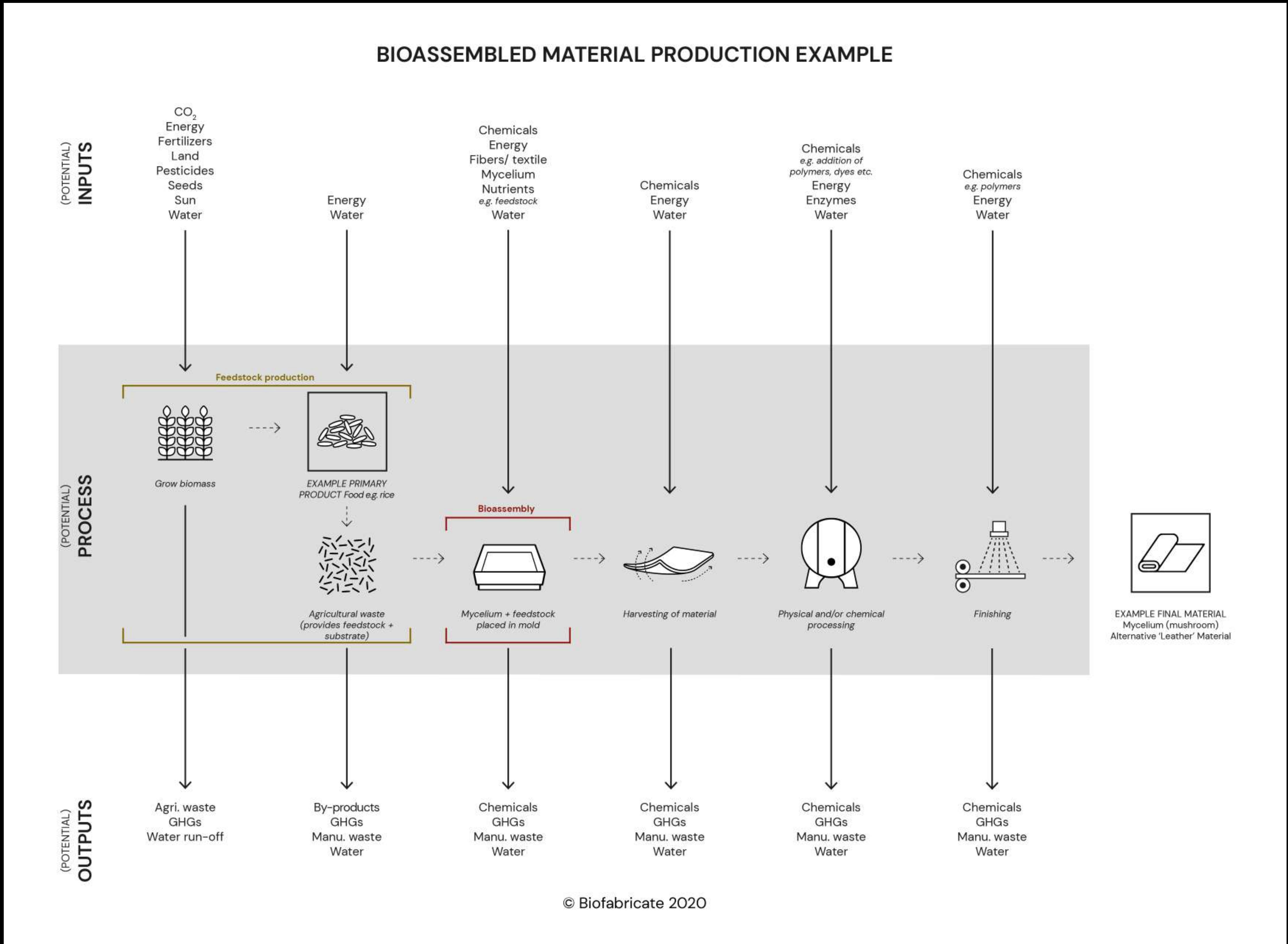


Figure 3: Bioassembled Material Production Example Diagram

A key area of misalignment and tension can come in the form of material targets and feedback. While some larger luxury and sport brands will have inhouse technical expertise, most fashion brands won't, and in very few cases is it likely to match the more fundamental scientific knowledge of many early stage startups. This can set up a disconnect during material development where samples are generated to advance iterative scientific understanding with less focus on performance or aesthetic.

Startups need to find ways to communicate how progress is being made when it may not always be obvious. Establishing early on what specific technical expertise a brand can offer will help to identify when and where additional resources should be sought. Material innovators are also urged to acquire an understanding of where their product fits within the target supply chain and what tolerances, if any, might there be for changes in manufacture.

Finally, all involved should be mindful that exclusivity deals, while helpful initially for innovators and brands, need to be of short duration if they are not to inhibit the wider adoption of these materials for the benefit of all. Consortia of brands can help innovators in this regard to spread risk, as evidenced by Bolt Thread's recent announcement of Mylo partners: adidas, Kering, Lululemon and Stella McCartney.

WHY CAN'T I BUY THESE MATERIALS NOW?

The demand for new biomaterial innovations currently massively outstrips supply, especially in the newer biofabricated sector. This is exacerbated by the perception painted by the media on the market readiness, as opposed to the actual maturity and technology readiness level of most startups.

A common misconception is that these radical new material innovations are 'just around the corner'. While this may now be true of a few companies, who have already labored for a decade or more, the majority of promising innovations are much earlier in their journey. Setting unrealistic expectations is a disservice to both innovators, brands and their customers, with the potential to impact the success of the field in general.

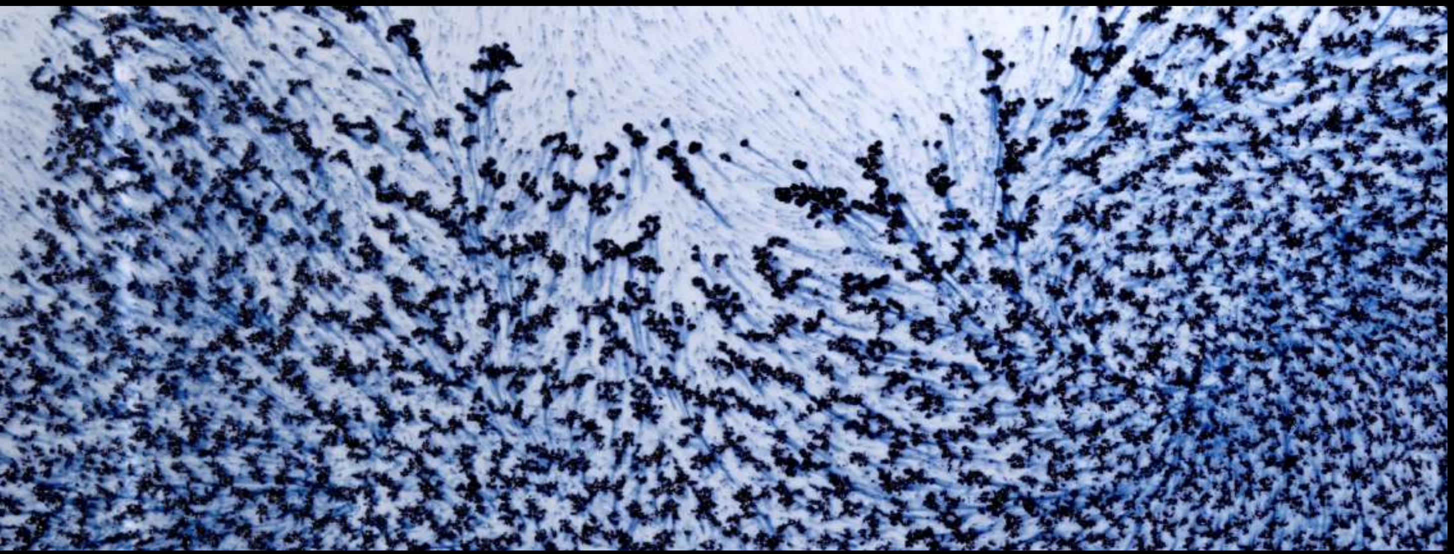


Image: PILI Bio

Biomaterial innovation remains a relatively young field and most startups were established within the last decade. The first few, pioneering biofabricated solutions are only now on the cusp of commercialization and brands outside existing exclusive partnerships will no doubt have a few more years to wait before they are able to access the materials they are reading about today.

RECOMMENDATIONS

Above all else, this report recommends patience and perseverance. The environmental problems of the fashion industry were not created overnight and the solutions won't be either. Only by having honest and transparent partnerships can we accelerate change. The timeline for material innovation is measured in years not months, and in many cases it will be close to a decade (if not longer) before many materials reach volumes with potential for global impact.

ABOVE ALL ELSE, THIS REPORT RECOMMENDS PATIENCE AND PERSEVERANCE. THE ENVIRONMENTAL PROBLEMS OF THE FASHION INDUSTRY WERE NOT CREATED OVERNIGHT AND THE SOLUTIONS WON'T BE EITHER. ONLY BY HAVING HONEST AND TRANSPARENT PARTNERSHIPS CAN WE ACCELERATE CHANGE.

The complexity of developing biomaterial innovations varies significantly. Biofabricated materials specifically, are challenged in multiple dimensions; from the complexity of the R&D needed, the costs of developing these technologies, the long timelines involved moving from lab > bench > pilot/demonstration > commercial scale, through to the high performance, aesthetic and manufacturability requirements of materials for the fashion and textile sectors.

Closer partnerships between material innovators and brands will help to ensure that products are developed which truly meet the needs and standards the industry expects whilst also providing a more equitable sharing of resources and expertise, both financial and in kind. Where brands do not have specific technical expertise in house they need to assist innovator partners with access to key supply chain associates, supporting those relationships throughout.

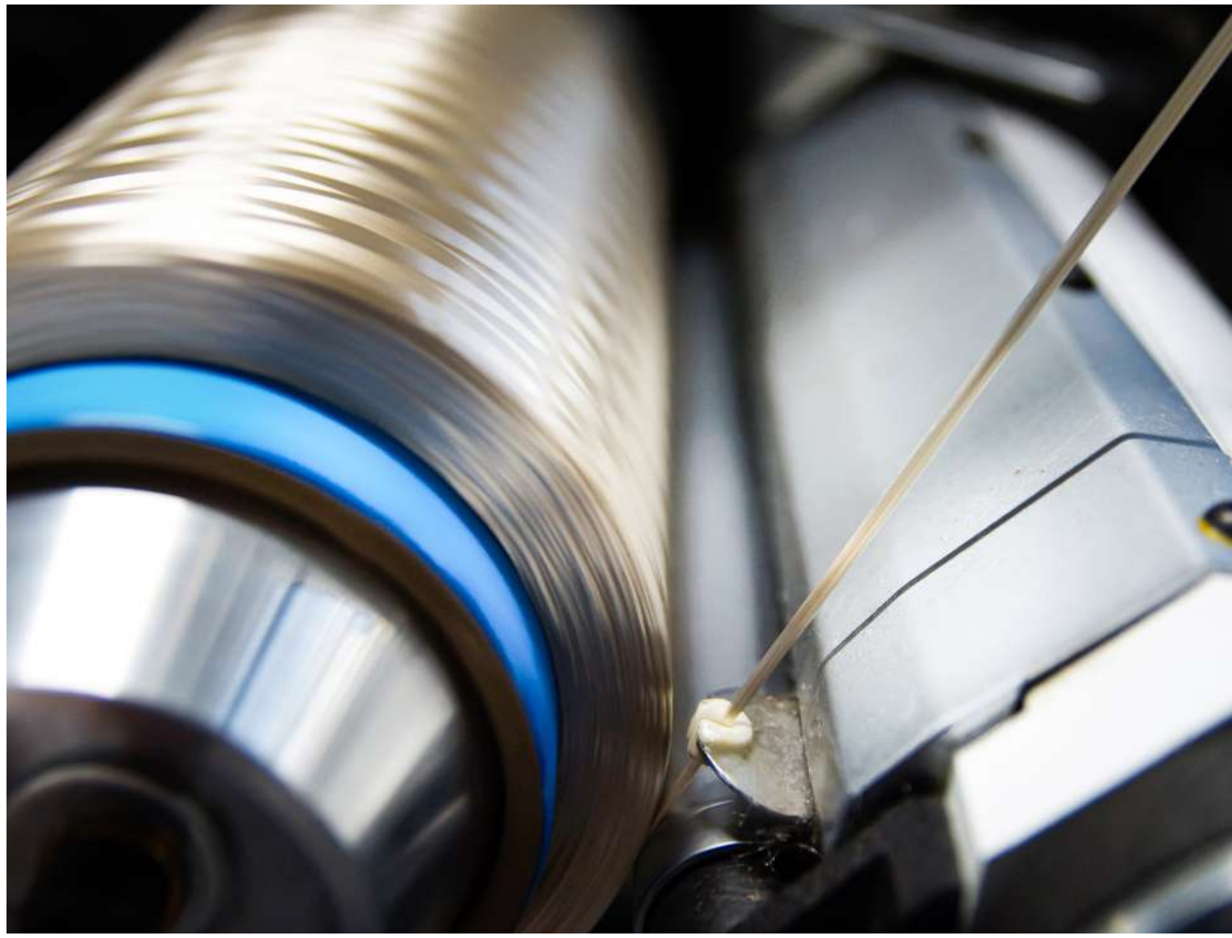
We recommend the fashion industry moves to align on language as relates to bio innovations for the benefit of brands, innovators, investors and ultimately consumers. We also suggest the use of process diagrams, such as those we have created here, to understand different biomaterial innovations and to enable transparency, discussion, and comparison in a world of confusion and misinformation. As more materials come to market there will be a need for increased communication efforts to help customers understand the different purchasing choices available and their potential impacts. Where and how further standards and guidelines might be required for emerging biomaterial categories will likely be an ongoing conversation for the fashion industry.

Finally, we recognize that two key concerns arise in discussion of biomaterials; use and treatment of genetically modified organisms and end of use. Although beyond the scope of this research, both are important and complex areas deserving of their own reports.

CONTENTS

INTRODUCTION & CONTEXT

THE SAME QUESTIONS ARE ASKED BY SO MANY BRANDS, MEDIA AND INVESTORS: **WHAT IS ACTUALLY MEANT BY THESE DIFFERENT TERMS?**, WHAT DO THESE MATERIALS CONTAIN?, HOW THEY ARE MADE?, HOW DO THEY DIFFER?, WHICH HAVE GREATER ENVIRONMENTAL IMPACT?



Images:
L: Mylo™, Bolt Threads
R: Brewed Protein™, Spiber

INTRODUCTION & CONTEXT

This report was prompted by a question at Biofabricate's London 2019 summit asking if there are any guidelines or standards for the emerging field of biofabricated materials. The short answer is: there aren't. Nor are there any fully scaled biofabricated materials on the market at the time of writing. The desire for more information is not just tied to biofabricated materials, there is a general lack of understanding across the fashion industry with regards to biomaterials. The same questions are asked by so many brands, media and investors: what is actually meant by these different terms?, what do these materials contain?, how they are made?, how do they differ?, which have greater environmental impact?, and so on.

Before guidelines or standards might be established for any one category of biomaterial, it is clear that we first need to understand how we classify different biomaterials, their processes and what our expectations are of them. Do specific descriptors come with an expectation of biocontent or end of use?

Biofabricate joined forces with Fashion for Good to collaborate on a report that would not only aim to bring clarity to this subject area, but also to go deeper and examine what success looks like between brands and innovators bringing new biomaterials to market. The report leverages these two overlapping but discrete networks to gather insights and understanding from a broad group encompassing leading material innovators along with fashion, sport and luxury brands, manufacturers and industry partners.

The report is an independent effort, it has not been sponsored by any external brand or body. Together, the team has sought to balance the perspectives of both innovators and brands.

REPORT PROCESS

The report is a qualitative assessment seeking to define what is meant by a series of still evolving "bio" terms for the fashion industry and their associated implications. How does new language borrowed from the biomedical domain, such as "biofabricated" and "bioassembled", represent radically different technologies to "biobased" or "biosynthetic"? What are the divergences in feedstock, process, inputs, outputs and impact hotspots for each? What are the key considerations when scaling these newer innovations? The team conducted a focused literature review of government resources (US and EU) cross referenced with industry bodies, scientific papers, and common use examples by startups and brands. The report arrives at definition recommendations for "bio" terminology relating to the fashion industry, as well as indicating the types of feedstocks and processes that are commonly suggested by each term.

While exploring specific challenges related to biomaterial innovation, it uncovers and shares insights beneficial to both material innovators and consumer brands alike as more partnerships are formed to channel innovation through to the consumer. The analysis synthesizes key learnings from 32 industry experts in this space, the majority of which come from material startups, followed by brands already active in this space, as well as other manufacturers and industry stakeholders. The startups represent a broad selection of private companies varying in commercial readiness from seed stage through to roughly series D.

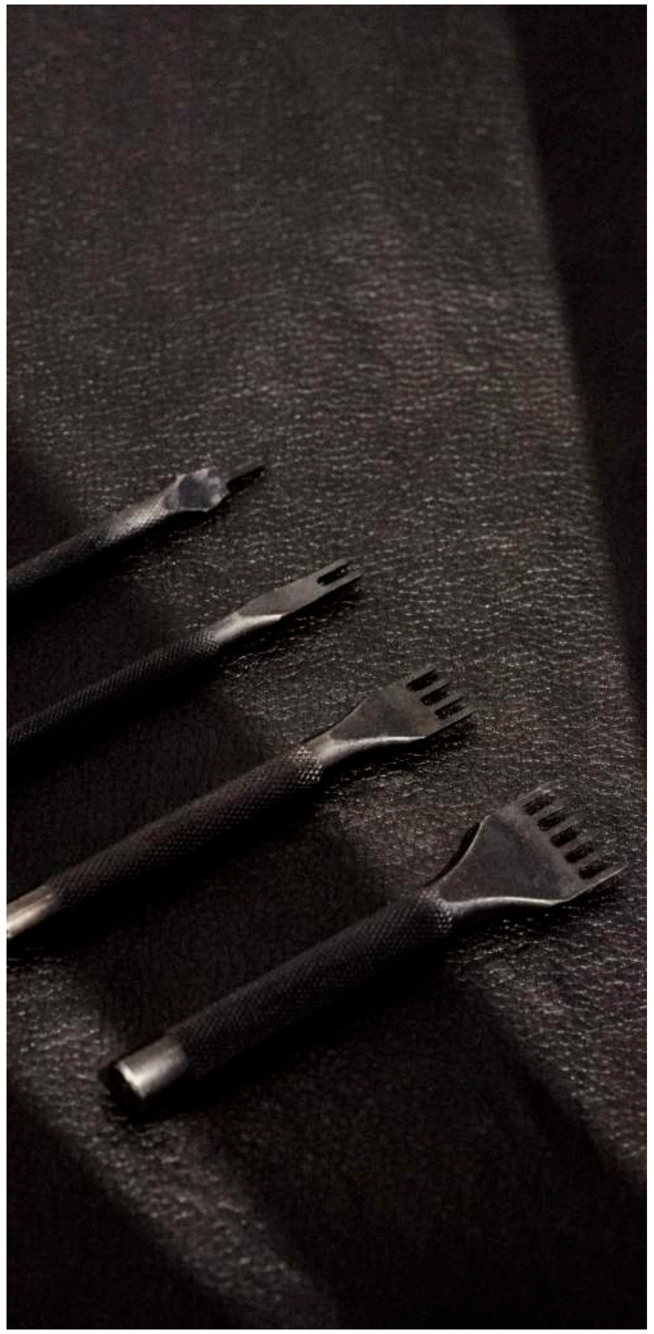


Image: Courtesy of Made with Reishi™ by MycoWorks

INTERVIEW PROCESS

- The team reached out to each expert inviting them to participate in a 60 minute interview
- Interview questions for both innovators and brands can be found in Appendices 1 and 2
- Interviewees were informed that interviews would be recorded, that all results would be anonymized, and that consent would be sought for any direct quotes used in the report
- In advance of each interview the interviewee received a preread with initial thoughts on definitions for reaction
- Each interview was conducted with representatives from Biofabricate and / or Fashion for Good
- Responses were collated into a key learnings document capturing specific quotes where relevant (these have been edited with the participants permission and approval)
- Understandings and use of bio terminology across the group was synthesized to provide clarified definition recommendations for the industry

Alongside these interviews the team sent out surveys to additional innovators working in this space, asking the same interview questions that the interviewees were asked. A further seven responses were received. All responses to those further surveys have been anonymised in the report.

REVIEW PROCESS

- The draft report was circulated to all interviewees for their review
- Feedback from each interviewee was recorded and assessed
- Where relevant, feedback was incorporated into the report before publication

IN SCOPE

This report specifically focuses on the topic of biofabrication and the different feedstocks and processes included under that term. It includes the following:

- **Definitions of the terms: biomaterial, biodesign, biobased, biosynthesis, biosynthetic, biofabrication, bioassembly -** an analysis leveraging existing definitions and industry knowledge. The newer terms biofabricated/bioassembled include analysis as to where these terms originate and how they are understood in the industry today.
- **Process diagrams:** diagrams that map out different biomaterial production processes, as well as listing indicative inputs and outputs which can help to identify possible impact hotspots.
- **Developing biofabricated innovations, R&D and Scaling:** qualitative analysis exploring the roadmap to scale, R&D timelines, material development choices, impacts and end of use, scaling and technology readiness and supply chain readiness.
- **Partnerships:** insights into what makes for successful partnerships in this space including types of partnerships, material development, samples and progress.
- **Impact analysis**: including lifecycle and impact assessments and the role they play in the development roadmap and impact hotspots.
- **Key Learnings**: key learnings and useful questions brands / innovators can ask each other to build a stronger collaborative partnership.

OUT OF SCOPE

There is a series of topics that are beyond the scope of this report and are not explored in detail as part of this analysis. These include:

- **Strategic Recommendations**: it does not provide strategic recommendations for readers, or advocate for one process or innovator over another.
- **Detailed sustainability impact assessment**: sustainability is referenced in this report based on interviews and desk research. We have not attempted to quantitatively measure the environmental impact of the different biomaterial processes. However, through our research we have identified common environmental impact hotspots that can be a starting point for further evaluation.
- **GMO/non GMO**: the topic of genetically modified organisms (GMO's) surfaced in a number of interviews. Some information on this is included at the end of this report as an opportunity for further research, but any further analysis is outside the scope of this report. We recognize this is a nuanced and complex area deserving of its own deeper analysis.
- **End of use**: the topic of end of use including compostability, biodegradability and recyclability was flagged as an area that often lacks transparency within the context of biobased solutions but any further analysis is outside the scope of this report. End of use is when the product reaches the end of its lifespan and is no longer in use by its owner. The term 'end of life' is often used in this context but suggests that the product has no other use after this lifespan. However, within a circular economy, the aim is to keep a product and materials in use for as many cycles as possible. either through recycling or by re entering the biosphere through composting or degradation[2].

As outlined in this introduction, the main goal of this report is to align on definitions of these new 'bio' materials, and focus on the technologies that enable their production, not to classify the end materials.

However, having received multiple questions about where these materials sit in relation to existing materials, (e.g. natural fibers such as cotton or manmade cellulosics such as viscose) we have added a first pass at placing these materials within the established textile classification system. This is intended as a conversation starter on this topic; deeper industry discussion and alignment is needed.

A biofabricated material could be comprised of, for example, protein, cellulose or a biosynthetic polymer. The process of biofabrication does not automatically denote how the end textile would be classified. They would all fall under different categories of textile classification.

The textile classification diagram presented here (figure 4), is based on the industry accepted groupings[3,4] as defined in legislation such as the Textile Fiber Products Identification Act[5] (TFPIA) in the USA.

This system is an imperfect tool to apply here. It is traditionally used for textile fibers and therefore materials like leather are omitted. While this means the inclusion of mycelium as an alternative to leather is potentially problematic, it has been added here so that the main types of materials covered in this report are represented.

Mycelium has been placed under manmade natural polymers. The reasoning for this is that only the root system of the organism is being cultivated, preventing it from fruiting (which would not occur in nature). This requires specific, engineered, growth conditions and processing. Other additions of note are biosynthetics, which have been included as a new group under synthetic materials to differentiate from petrochemical derived synthetic materials.

This is a first attempt to classify this new category of materials (all of which are called out in blue). The authors welcome feedback on the diagram.

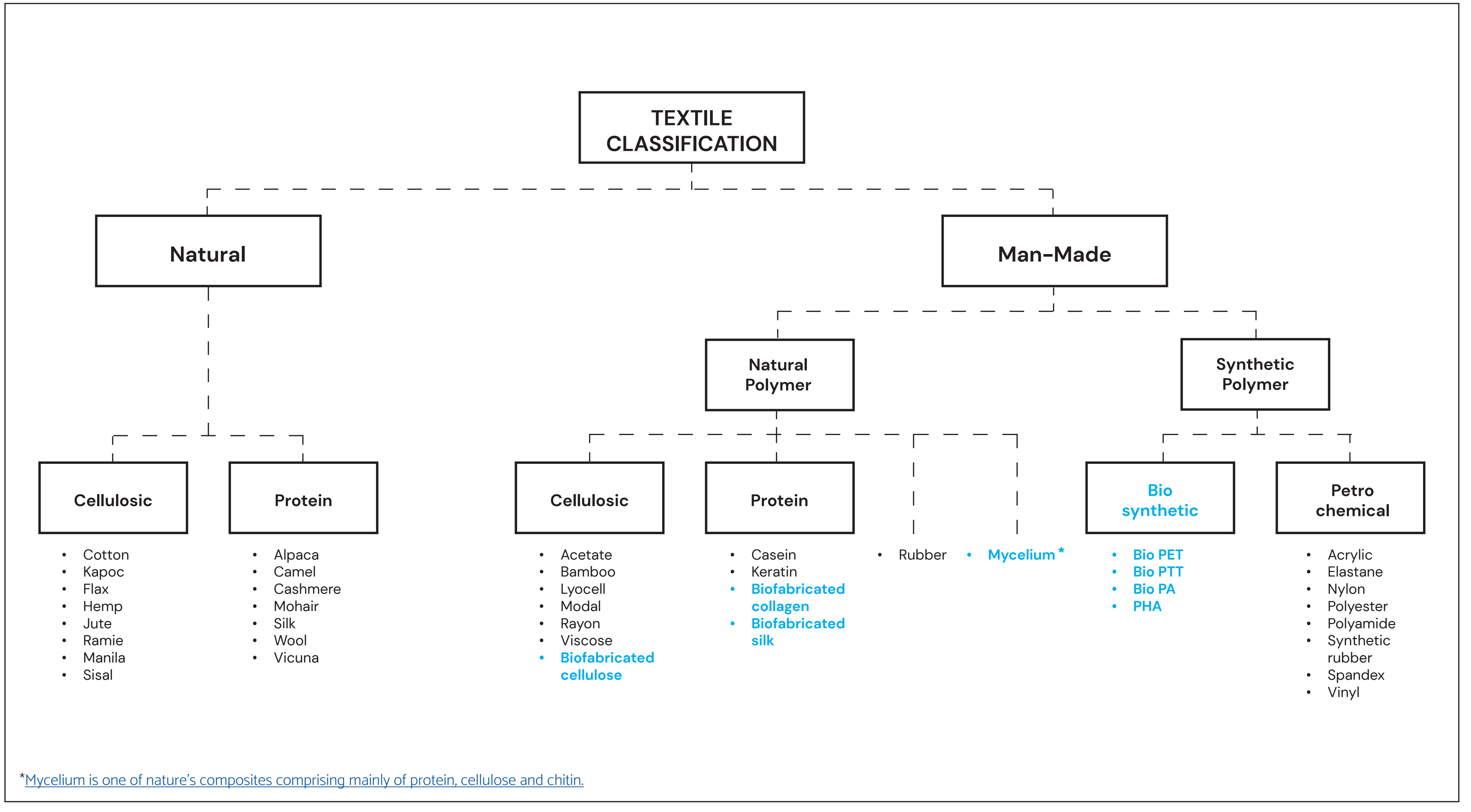


Figure 4:
Textile Classification Chart

DEFINITIONS CONTEXT

IN RECENT YEARS, AND WITH INCREASING FREQUENCY, VARIOUS **"BIO"** PREFIXED WORDS HAVE ENTERED THE LEXICON OF INDUSTRIES RANGING FROM OUTDOOR APPAREL AND PERFORMANCE SPORT TO LUXURY FASHION.

Images:
L: Biofabricate Summit 2019, Biosteel®, AMSilk, photo by Chloe Hashemi
R: Stahl

DEFINITIONS CONTEXT

In recent years, and with increasing frequency, various "bio" prefixed words have entered the lexicon of industries ranging from outdoor apparel and performance sport to luxury fashion. They include the likes of "biobased", but also "biomaterial", "biotechnology", "biosynthetic", "biofabrication" or "biodesign", among others.

The introduction of this new language to the fields of fashion and textiles stems from multiple places. It emanates from material innovators; startups explaining their technologies (via their websites, public presentations and media interviews), it comes from brands seeking to understand and communicate innovation to their own internal teams and their customers, and it is widely spread by the media. It is further cemented in the industry when it appears as a category in trade fairs, in trend forecasting reports etc. It should also be noted that in parts of Europe "bio" also indicates "organic", however for the purposes of this report we use the 'bio' prefix to represent biology in its broadest sense.

Evidently, there is a general lack of aligned understanding of these "bio" terms, and, in its absence, many cases of incorrect use causing confusion all round. Due to the vagueness of a term like "biomaterial", generalized assumptions are made such as; "if it's 'bio' it must be better", or "if it has 'bio' in the name it must be biodegradable". With so much global focus on environmentally sound solutions and well intentioned brands and consumers seeking to make the "right" choices, it behoves both innovators, material manufacturers and brands alike, to address the language they use to explain the different technological processes they employ and the relative merits of the materials produced.

From our conversations with innovators for this report, it is clear that even amongst the scientific community there are variations in the understanding of words relating to specific (bio)technological processes or products - precisely because no standard agreed definitions exist. This is further complicated by words that have existing meaning in one field of science, being appropriated and widely adopted in totally different contexts and industries, as is the case with the terms "biodesign", "biomaterial" and "biofabrication" (as explained in section 2).

The report authors recognize "bio" terms, as with all language, are evolving over time. In the absence of any expert informed, existing reference[6] of "bio" terminology for the fashion industry, we have attempted to bring together a review of terms, and via a series of diagrams, the different processes they represent. We hope this provides a useful foundation that can be built on as more of these materials enter the market.

The work we have done here, seeking input from both innovators and brands to understand and refine language, is foremostly intended to help with B2B relationships. It is to assist material startups, brands, manufacturers and investors in speaking a common language, to align on goals for material innovation, to enable deeper partnerships, to drive internal education, and equip communications teams as they disseminate their innovation stories to the media and wider public. We imagine that further simplified or even alternate language will be used to speak to the final end customer; the consumer.

Images:
L: Stella McCartney x Bolt Threads
R: Stella McCartney x Bolt Threads, Mylo™ Falabella Prototype One

DUE TO THE VAGUENESS OF A TERM LIKE "BIOMATERIAL", **GENERALISED ASSUMPTIONS** ARE MADE SUCH AS; "IF IT'S "BIO" IT MUST BE BETTER", OR "IF IT HAS "BIO" IN THE NAME IT MUST BE BIODEGRADABLE."

MOTIVATIONS & ADOPTION

The risks in not having widely agreed upon definitions are that important nuances are missed. For example, the ability of different terms to indicate variation in environmental impact through inputs and outputs of a particular technology and a product's end of use. Ambiguity around "bio" terminology also lends itself to opportunistic manipulation of language to suit a specific interest, or conversely, that all the terms become meaningless if used interchangeably, thus benefiting no one.

Even where there is a pre existing academic definition, in a commercial context there are various reasons why that language may not be adopted. A material innovator may reason what language would best serve their company in the following dimensions:

1. **For customer education** - What words will best facilitate customers or, in some cases, consumer, understanding of our technology or product?
2. **For market positioning** - What terminology will best drive our ability to position and compete within a certain established (or novel) category of materials? How can we harness this positioning to maximize financial return?
3. **For brand positioning** (innovators) - How do we hone our language to cement the perceived value we're looking to establish in order to attract the brand partners we desire?

So while a material technology may fit a scientific definition of, say, "biosynthetic", the choice may be made to not use the word "synthetic" anywhere, because in the field of fashion/textiles it might imply something less natural, or of lesser value, or otherwise confuse a potential partner from outside their technology domain.

To summarize, the decision to apply a certain word to a technology or product may not only be based on scientific accuracy. It may be driven by economic motivations, it may include weightings for brand or market positioning, or for simpler business to business/ direct to consumer (B2B/DTC) communications.

READINGS OF 'BIO' TERMS

The following section dives into definitions of 'bio' prefixed terms. As will be discussed, some of these definitions may be sanctioned internationally in the form of ISO standards, by geographies or governments (EU, USDA), by academia (often within a relatively narrow field), or, more loosely, by a special interest industry group.

However, as words permeate popular culture, they often end up being used more broadly, moving away from their original meaning or even representing something quite different than intended. We have found there may be several 'readings' of some of these definitions and their real world application:

1. **A high-level, *generalized* reading of "bio" + "WORD".**
   This reading is the most expansive, is open to interpretation, and is thereby highly limited in its specificity.
2. **An *adapted* reading of an established definition.**
   This reading may reference another field (such as biomedical) but reinterpret and apply it to represent a much broader context.
3. **A *literal* reading.**
   This reading stays close to an established definition.

Image: **ZOA™, Modern Meadow**

TO SUMMARISE, THE DECISION TO APPLY A CERTAIN WORD TO A TECHNOLOGY OR PRODUCT **MAY NOT ONLY BE BASED ON SCIENTIFIC ACCURACY**. IT MAY BE DRIVEN BY ECONOMIC MOTIVATIONS, IT MAY INCLUDE WEIGHTINGS FOR BRAND OR MARKET POSITIONING, OR FOR SIMPLER B2B/DTC COMMUNICATIONS.

DEFINITIONS

THE FOLLOWING SECTION DIVES INTO DEFINITIONS OF "BIO" PREFIXED TERMS. AS WILL BE DISCUSSED, SOME OF THESE DEFINITIONS MAY BE SANCTIONED INTERNATIONALLY IN THE FORM OF **ISO STANDARDS**, BY GEOGRAPHIES OR GOVERNMENTS (**EU, USDA**), BY ACADEMIA (OFTEN WITHIN A RELATIVELY NARROW FIELD), OR, MORE LOOSELY, BY A SPECIAL INTEREST **INDUSTRY** GROUP.

Images:
L: Courtesy of Made with Reishi™ by MycoWorks
R: Huue

DEFINITIONS: BIOMATERIAL

Image: Courtesy of Made with Reishi™ by MycoWorks

WHEN WE ASKED "IF A MATERIAL HAS SOME KIND OF 'BIO' PREFIX IN THE NAME **WHAT PERCENTAGE OF BIOCONTENT SHOULD IT CONTAIN?"**, MOST INTERVIEWEES EXPRESSED IT SHOULD BE A MINIMUM OF **50% BIO-CONTENT.**

In the field of fashion, the term "biomaterial" is generally used to describe an end product; a finished material. It should be noted however, that online searches usually only return a medical definition, which is confusing and shows how nascent the term is in relation to apparel textiles or leather alternatives. The biomedical definition encompasses materials which may be biocompatible metals and plastics. To further complicate matters, our review found examples of the word biomaterial being applied to both materials from nature (biopolymers), such as wood[7], as well as to biosynthetics, such as DuPont's Sorona[8] product.

Outside of the medical field, academic definitions for "sustainable biomaterials"[9] range from "Biological materials in a variety of scales and types" to "the use of natural, renewable resources to produce innovative materials and bioenergy in a sustainable manner[10]."

The general assumption in fashion, is that a biomaterial either contains biomass, or biologically derived ingredients, or was made using some kind of biological process, or is biodegradable, or all of the above.

From our interviews, some innovators felt that the term biomaterial was either vague or too generic, with no indication of bio content. Others suggested that if it is used to describe a material that also includes synthetic polymers from fossil fuels, that it is misleading unless it indicates what percentage of bio content it contains. Without this qualification it 'feels like greenwashing'.

When we asked "if a material has some kind of 'bio' prefix in the name what percentage of biocontent should it contain?", most interviewees expressed it should be a minimum of 50% bio-content. This suggests, by extension, that a biomaterial should be majority bioderived.

The term biomaterial does however appear to be widely used, with familiarity to the word but not what it represents. Does it imply a material contains biocontent (if so how much)?, that it's made with a biological process? or that it is biodegradable? or all of the above? or some of the above?

"Biomaterial" today is an increasingly common shorthand term to indicate a material has something of a biological association but without providing any specifics. This ambiguity, while perhaps useful for marketing purposes, is problematic if trying to understand the relative merits of biomaterials from different suppliers, or indeed for innovators wanting to differentiate their technology versus that of a competitor who is perhaps using a less sophisticated/cheaper/less sustainable technology. In conclusion, the word biomaterial suggests a need for more context or further qualifiers.

This report puts forward the following recommended definition:

BIOMATERIAL:
"Biomaterial" is a term used to indicate materials that have non specific biological association."

DEFINITIONS: BIODESIGN

"Biodesign" is one of the words that the design industries have coopted from the biomedical field. In 2009 Stanford University faculty published (via The Cambridge University Press) the first textbook[11] called "Biodesign - The process of innovating medical technologies". The focus of both the book, the faculty, and the field historically, has been health technology innovation. In the sciences, sometimes the term "bioengineering" is used interchangeably with biodesign.

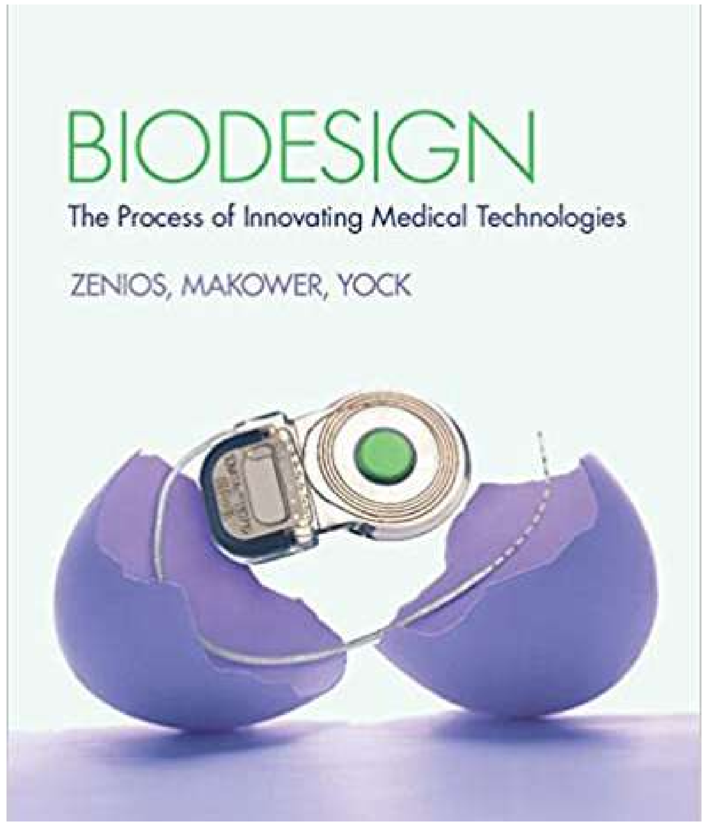
However, as non medical designers were introduced to, and employed, living systems in the form of cells, organisms, biological materials and technologies, the term biodesign started to be applied to work at the broader interface of design and biology. These design projects, mostly unrelated to health technology innovation, were initially captured in another, very different book[12], also called "Biodesign", this time by curator William Myers, published by The Museum of Modern Art and Thames & Hudson, with the subtitle "Nature, Science, Creativity". Myer's definition of biodesign is as follows:

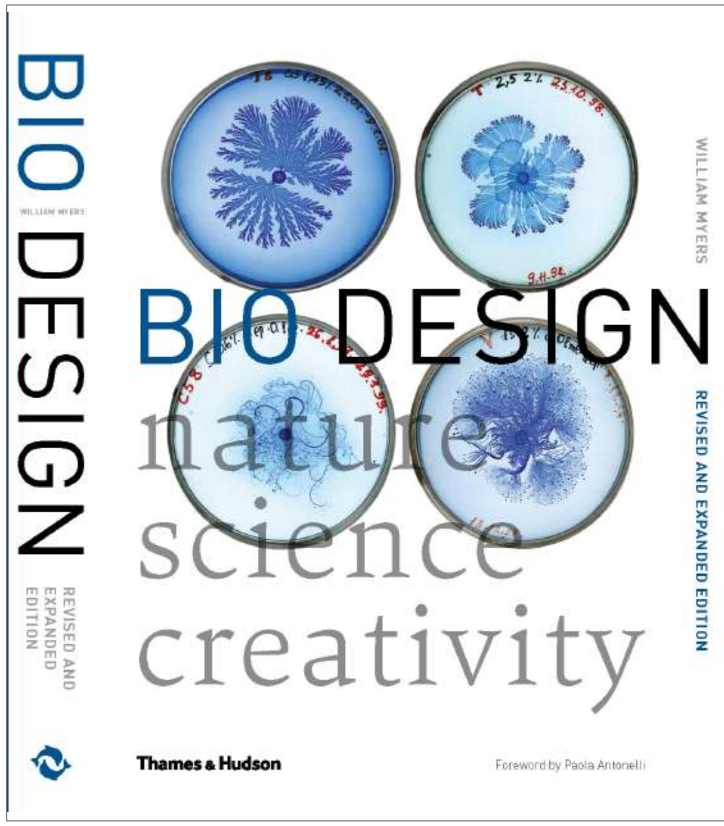
"Biodesign is the next step beyond biology inspired approaches to design and fabrication. Unlike biomimicry or the popular but vague "green design," biodesign refers to the incorporation of living organisms as essential components in design, enhancing the function of the finished work. Biodesign leaps ahead of imitation and mimicry to integration and use, dissolving boundaries and synthesizing new hybrid objects and architecture."

The above definition and understanding is now being enacted in leading art and design schools[13] around the world to encompass the study of design and biology with application in everything from advertising and architecture to food and fashion.

Common usage of the term "biodesign" outside of the field of medicine, mostly falls into the following categories: design *of* biology - at biotechnology companies such as Ginkgo Bioworks, their "organism designers[14]" "design" or "write" the DNA code that determines what a cell will be or do; design *for* biology - designing systems that manipulate biological growth for product benefits; designing *with* the product of biology - for example working with dyes and materials produced by living organisms, plus many projects that speculate on biodesign "futures" but which are not reality today.

As with all top level readings of our bio definitions and following the convention of the word "biotechnology": "biology" + "technology", "biodesign" could also simply be defined as "biology" + "design".





Images:
L: Biodesign The Process of Innovating Medical Technologies, Cambridge University Press
R: Biodesign: Nature, Science, Creativity, Thames & Hudson

This report puts forward the following recommended definition:

BIODESIGN:
"Biodesign' is a term used to indicate design 'of', 'for' or 'with' biology."

"BIODESIGN IS THE NEXT STEP BEYOND BIOLOGY-INSPIRED APPROACHES TO DESIGN AND FABRICATION."

WILLIAM MYERS, AUTHOR 'BIODESIGN: NATURE, SCIENCE CREATIVITY'

DEFINITIONS: BIOBASED

"THE TERM **BIO-BASED** PRODUCT REFERS TO PRODUCTS WHOLLY OR PARTLY DERIVED FROM BIOMASS, SUCH AS PLANTS, TREES OR ANIMALS."

Biobased, or bioderived, products are deemed to provide an alternative to conventional petroleum derived products. Biobased commercial or industrial goods are defined by the United States Department of Agriculture (USDA[15]) as:

"(A) composed, in whole or in significant part, of biological products, including renewable domestic agricultural materials, renewable chemicals, and forestry materials; or (B) an intermediate ingredient or feedstock"

Europe[16] uses a similar definition:

"The term bio-based product refers to products wholly or partly derived from biomass, such as plants, trees or animals (the biomass can have undergone physical, chemical or biological treatment)."

The USDA has instigated a "BioPreferred Program" "to assist in the development and expansion of markets for biobased products". Products need to meet a minimum biobased content set by the USDA, and manufacturers must test the biobased content at an independent, third party laboratory. Part of this initiative is voluntary product certification and labeling with thousands of products being listed in hundreds of categories. The USDA "Certified Biobased Product" label is designed to provide useful information to consumers about the biobased content of the product. The label assures a consumer that the product contains a USDA verified amount of renewable biological ingredients.

Image: **Evolved by Nature**

However, not all biobased products are held to the same standard when it comes to the percentage of biocontent it must contain in order to be classed as biobased. The required minimum percentage of biocontent is published in a catalog of product categories[17]. As an example[18], a biobased disposable cup must contain a minimum of 72% biocontent while a biobased carpet only needs to have 7% biocontent. Fibers and fabrics are required to have a minimum of 25%.

EN 16575 ("Biobased products - Vocabulary"), a standard defining general terms to be used in the field of biobased products, was published by the European Committee for Standardization (CEN) in August 2014. However, the European Commission has identified a lack of European standards for biobased products, in particular for the determination of biobased content. It has issued several standardization mandates to the CEN[19] which has working groups focused on several product areas. Standards for biobased products are seen to help increase market transparency by providing common reference methods and requirements in order to verify claims about these products (e.g. biodegradability, biobased content, recyclability, sustainability).[20]

There is an existing definition for biobased materials and products:

BIOBASED:
"The term bio-based product refers to products wholly or partly derived from biomass, such as plants, trees or animals (the biomass can have undergone physical, chemical or biological treatment.)"[16]

DEFINITIONS: BIOSYNTHESIS

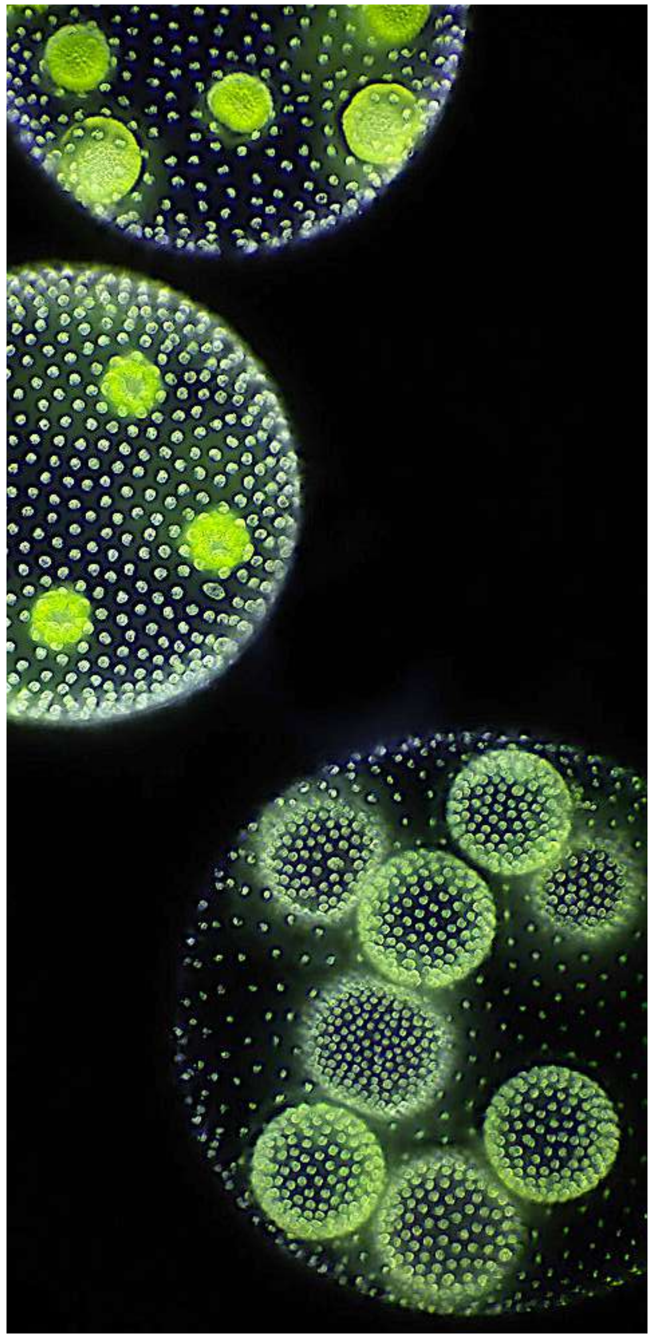
MANY COMPANIES PRODUCING “BIOMATERIALS” WILL BE USING “BIOSYNTHESIS” SOMEWHERE IN THEIR PROCESS. THE **COMPOUNDS RESULTING FROM BIOSYNTHESIS CAN BE EITHER “SYNTHETIC” OR “NATURAL”**.

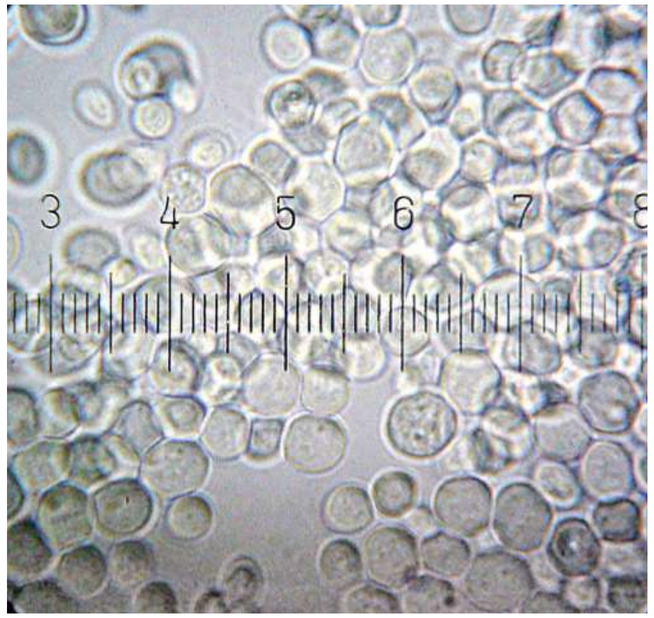
In the natural world, “biosynthesis” is occurring all the time, everywhere. Biosynthesis describes the production of complex chemical compounds from simpler molecules. This happens inside the cells of living organisms such as bacteria, plants and animals.

Many companies producing “biomaterials” will be using “biosynthesis” somewhere in their process[21]. The compounds resulting from biosynthesis can be either “synthetic” OR “natural”.

Biosynthesis is a process. The intention of some biosynthetic processes is to create biobased “drop ins” for existing petrochemical derived materials[22]. The goal is to use an alternative, bioprocess, to create a *synthetic* polymer that is chemically similar or identical to, for example, polyester. The resulting materials are typically called “biosynthetics”.

However, other companies may use biosynthesis to produce *natural* polymers like cellulose or silk. To call these materials “biosynthetic” therefore becomes confusing in a fashion textiles context due to the association with synthetic materials (see biosynthetics below). The goal of these companies is to produce the same polymers found in nature, those previously derived from plants or animals, but now within a different type of living organism; eg a microbe which produces a “spider silk protein”. These would be better described as “biofabricated” as a broader category.





This report puts forward the following recommended definition:

BIOSYNTHESIS:
“Biosynthesis is the process by which a living biological organism or cell transforms simple molecules into complex ones.”

Images:
L: Frank Fox / CC BY-SA 3.0 DE
R: Bob Blaylock / CC BY-SA 3.0

DEFINITIONS: BIOSYNTHETIC

Image: Genomatica

TO SUMMARISE; "BIOSYNTHETIC" IS **A TERM WHICH IS USED TO DESCRIBE A SYNTHETIC MATERIAL** WHERE EITHER THE ***INPUT*** IS OF BIOLOGICAL ORIGIN, AND/OR WHERE THE ***PROCESS*** IS PERFORMED BY A LIVING ORGANISM (BIOSYNTHESIS). BOTH RESULT IN AN END MATERIAL THAT CAN BE TERMED ***"A BIOSYNTHETIC"***.

The standalone term "synthetic", as understood in the fashion and textile industry, refers to fully manmade fibers or fabrics derived not from agricultural or animal ("natural") sources but rather from fossil fuels. DuPont"s first fully manmade "synthetic" was an "artificial silk" which became known as Nylon. The publicity stated the new fiber was derived from coal, water, and air. Today the fossil fuel origin is more likely to be petrochemical, from crude oil. Other synthetics followed, including polyester, acrylic and spandex.

Synthetics are generally created by chemically *synthesizing* polymers which can be extruded into fibers and then woven, knitted etc. So chemical *synthesis* is the process, but the resulting materials are also known as *synthetics*.

For "biosynthetics", instead of deriving the building blocks of manmade, synthetic materials, like nylon, from a crude oil origin, the same building blocks are derived from a biological origin. For example, sugar is converted into a compound using chemical synthesis. This compound is then further transformed into a polymer that is chemically identical to that of fossil fuel origin, and therefore can be a "drop in" to synthetic fiber production.

In another biosynthetic scenario, a living organism is involved; a precursor to nylon 6,6 can be fermented within a microbe using sugar as a feedstock. The sugar is a renewable feedstock from a crop like corn. In this instance a microorganism, such a bacterium, feeds on the sugar nutrient and *synthesizes* (or produces) the chemical compound. As before, this compound is then further transformed into a polymer that is chemically identical to that of fossil fuel origin, and therefore the resulting fibers and fabric will have the exact same or similar performance and end of use properties.

Accordingly, the addition of the "bio" prefix to the word "synthetic", could refer either to a biological input (such as a renewable feedstock like sugar), or it could refer to a biological *process* using a living organism to actually produce a compound (biosynthesis).

To summarize; "biosynthetic" is a term which is used to describe a synthetic material where either the *input* is of biological origin (biomass), and/or where the process is performed by a living organism (biosynthesis). Both result in an end material that can be termed "*a biosynthetic*".

It should be noted however, that while a material may contain a chemical compound which is 100% bio derived, it could still be blended further down the supply chain with content which is *not* of biological origin, i.e. still from a petrochemical source. This means the "bio" component of a finished biosynthetic material could be the lesser percentage, eg 35% biobased and 65% fossil fuel derived.

In the context of fashion textiles, a "biosynthetic", at its simplest, denotes a bio derived compound that can be manufactured into a synthetic polymer, fiber or fabric.

This report puts forward the following recommended definition:

BIOSYNTHETIC:
"Biosynthetics are synthetic polymer materials comprised, in whole or in part, of bio derived compounds. These compounds can either be made with an input of biological origin (biomass), and/or where the process is performed by a living microorganism."

DEFINITIONS: BIOFABRICATION

Images:
L: Courtesy of Made with Reishi™ by MycoWorks
R: Adidas by Stella McCartney, Bolt Threads Microsilk™

Within the family of "bio" terms, the most recent to be applied to the fashion industry is "biofabrication", also known as "biomanufacture". As with the terms biodesign and biomaterial, the term biofabrication has found adoption outside of its medical origins because it allows for a surface reading as simply bringing together "biology" with "fabrication", or, "fabricating with biology".

Several attempts have been made to shed light on the exact meaning and scope of biofabrication applied in different disciplines, mostly within the medical field. But with growing interest from other industries including food, materials science and textiles, there appears to be a persistent lack of clear and distinguished language addressing variations in different application areas.

To provide a holistic picture and understanding of what the term biofabrication entails and how it has evolved over time, this section takes a closer look at the field's origins and how it's moving from its initial application in the medical domain to find emergent usage in the field of fashion.

WITHIN THE FAMILY OF 'BIO' TERMS, THE MOST RECENT TO BE APPLIED TO THE FASHION INDUSTRY IS **'BIOFABRICATION'**, ALSO KNOWN AS 'BIOMANUFACTURE'

ORIGINS

The term biofabrication was first coined in 1994[23] to describe the "biomineralization" of pearls. Biomineralization is a naturally occurring form of biofabrication, but more recent interpretations include the application of technological manufacturing strategies as used in disciplines such as biotechnology and synthetic biology. It wasn't until 2009, and the inaugural issue[24] of the journal "Biofabrication", that the term was defined by Mironov et al as:

"the production of complex living and nonliving biological products from raw materials such as living cells, molecules, extracellular matrices, and biomaterials"

Mironov et al analyze and categorize biofabrication more specifically by firstly defining it as a technology, as opposed to a basic science, counting it in the wider field of biotechnology. Further, analysing the word biofabrication itself, the prefix "bio" implies that either raw materials, process, final products or all these factors are inspired by biology or biology based. Raw materials for biofabrication can be biological molecules, extracellular matrices and living cells and tissues. The term "fabrication" means making or constructing something from a raw or semi finished material or creating something that is different from its components. In this sense, biofabrication involves science, engineering and technology or production by using living matter as raw materials. A 2016 work by Groll et al[25] is a more recent comprehensive attempt to define the field of biofabrication. As a collective of representatives from the scientific community from fields including biology, chemistry, materials science, engineering and medicine, they jointly established a working definition of biofabrication while elaborating on key areas of recent activities in the field. Placing special emphasis on the link between biofabrication and two major areas of biomedical application, namely Regenerative Medicine and Tissue Engineering, the researchers defined biofabrication as:

"The automated generation of biologically functional products with structural organization from living cells, bioactive molecules, biomaterials, cell aggregates such as microtissues, or hybrid cell material constructs, through bioprinting or bioassembly and subsequent tissue maturation processes."

In the field of Regenerative Medicine and Tissue Engineering, the term biofabrication incorporates technologies such as bioprinting and bioassembly; foundational platforms for the 3D construction of tissues and organs in the human body. Bioprinting, a form of additive manufacture akin to 3D printing, uses mechanical deposition to position and manipulate living cells to build tissues. Bioprinting occurs at a molecular level, while bioassembly is articulated as starting from "minimum fabrication units of preformed cell containing building blocks with sizes large enough so that automated assembly can technologically be achieved."

Bioprinting is neither a scalable nor economically viable technique for the production of apparel textiles at this time. Bioassembly, however, allows for the formation of hierarchical structures fabricated by "cell driven self organization" and therefore the creation of materials at a macroscale relevant to consumer applications (see definition for bioassembly).

The other defining element in the (biomedical) biofabrication of materials is time: "a maturation phase" that allows the material to grow into a coherent structure. In the context of apparel this is more applicable to bioassembled materials as described in the next section.

In their reappraisal of the definition of the term biofabrication, Groll et al acknowledge that it is "an evolving research field[26]", that, at its most general, refers to:

"fabrication of materials by living organisms"[27]

Image: MOON PARKA by The North Face Japan (GOLDWIN Inc.) & Spiber

BIOFABRICATION IN THE FASHION & TEXTILE INDUSTRY

In the context of material fabrication for fashion, the "living organisms" referred to can include bacteria, yeast, algae, mycelium, and in some instances mammalian cells. Through processes such as fermentation, a microorganism or living cell "factory", produces an ingredient or material, but the organism or cell itself is not intended to be part of the final product. For example, a yeast cell might be used to produce a silk protein or a bacterial cell might be used to produce cellulose. In other instances, the organism is the material, it is either harvested and formed into a material (e.g. algae) or it grows and becomes the material structure itself (e.g. mycelium, mammalian tissues). In all instances the organism is terminated before further processing.

While all of the existing definitions for biofabrication are mainly applicable to the medical field, those broader in scope allow for the inclusion of disciplines beyond medicine including textile applications. The key similarities between the use of the term biofabrication in the biomedical field, and its appropriation by consumer material innovators are: both use living cells to produce biological ingredients or materials and both can involve use of bioreactors (such as liquid or solid state fermentation) to achieve the fabrication of materials by biology at different scales.

Three possible "readings" of the term "biofabrication" for the fashion industry might be:

1. **A high level, *generalized* reading: "biology + fabrication"**
   Such a reading might imply any process that is "fabricating with living biology".
2. **An *adapted* reading would be to adopt only the broadest existing definition: "fabrication of materials by living organisms"**
   Such a reading places emphasis on a living organism producing ingredients or materials, and presents a clear distinction from a material that is simply made of biological matter (biomass) but which involves no living cells in its production.
3. **A *literal* adherence to the definition as used by the biomedical field: "the production of complex living and non living biological products from raw materials such as living cells, molecules, extracellular matrices, and biomaterials".**
   This more specific reading was not created with the applications of textiles for fashion in mind (these operate at a vastly different scale) and therefore may not be as useful.

The second, adapted reading: "fabrication of materials by living organisms", is the definition that is perhaps most helpful for innovators wanting to distinguish materials they are producing using living cells and microorganisms.

It can be concluded that while the term biofabrication originates within the medical field, biofabrication technologies are evolving and extending into application areas including textiles for fashion. As alluded to in the beginning, there is a need for further clarification of various "bio" terminologies especially in relation to their application for fashion. The following definitions and illustrative diagrams for adjacent "bio" terms aim to provide further context and distinction.

Image: Brewed Protein™, Spiber

"FABRICATION OF MATERIALS BY LIVING ORGANISMS", IS THE DEFINITION THAT IS PERHAPS MOST HELPFUL FOR INNOVATORS WANTING TO DISTINGUISH MATERIALS THEY ARE PRODUCING USING LIVING ORGANISMS.

Images:
R: Colorifix
L: Modern Meadow

This report puts forward two recommended definitions:

BIOFABRICATED MATERIALS:
"Biofabricated materials are produced by living cells (e.g. mammalian) and microorganisms, such as bacteria, yeast and mycelium."

BIOFABRICATED INGREDIENTS:
"Biofabricated ingredients are building blocks produced by living cells and microorganisms e.g. complex proteins like silk or collagen. They need further mechanical or chemical processing in order to make a macroscale material structure."

Biofabricated ingredients may additionally include substances such as a dye being grown by a living cell or microorganism. The living microorganism may also be involved in the subsequent bioprocessing of the textile, for example in depositing a color and then fixing it.

DEFINITIONS: BIOASSEMBLY

As discussed in the previous section, "bioassembly" is a subset of biofabrication. Similarly to biofabrication, while a definition for bioassembly exists in the biomedical field, the use of the word in the broader sphere of consumer material innovation is far less cemented.

In the revision of the definition of the term biofabrication by Groll et al in 2016, bioassembly was distinguished by both scale and self organization. Among our interviewees, those with a clear view did indeed regard materials, rather than chemicals or ingredients, as the product of bioassembly. Specifically where a "macro" material structure is formed by a biological process.

Key aspects of the definition of bioassembly that track certain methods of material production for fashion applications are; "the fabrication of hierarchical constructs... generated via cell driven self organization", an example of which is mycelium leather materials.

In this emerging group of materials, the mycelium's threadlike "hyphae" self organize or grow into a densely formed self supporting sheet material structure at the macroscale. This growth may also be directed by regulating environmental conditions (and thereby controlling material properties such as flexibility). So whereas biofabrication may refer more generally to the use of living organisms like bacteria or yeast to produce complex molecular building blocks that can be purified and further transformed, via chemistry and materials science into materials, with bioassembled materials, biology is doing more of the work to build structure in an end material.

A further example of bioassembly are sheets of cellulose grown and formed by bacteria. Here, bacterial cells secrete nano fibrils of cellulose, which, during fermentation, self assemble into a ready formed sheet material. A final example of bioassembly is closer to the tissue engineering methods used in biomedicine, where mammalian cells are cultured and grown into materials. Multiple companies are currently harnessing bioassembly as they innovate materials for the fashion industry.

A word on the relative merits of one biofabrication method over another. Several people in our survey cautioned that it is not safe to assume that because a structure was produced by "nature" it will necessarily require less post processing to achieve desired performance, durability or aesthetic product benefits. Additional steps for chemistry and materials science may still be required and those inputs and outputs should also be factored.

So, where biofabrication generally deploys living organisms to fabricate the complex building blocks of materials, bioassembly, as a subset of biofabrication, is when those small fabricated molecules are further biologically assembled into micro or macroscale structures.

As with the term biofabrication, different levels of reading for bioassembly could be:

1. **A high level, *generalized* reading: "biology + assembly"**
   Such a reading might imply any process where a living organism is directly growing a material's macro structure.
2. **An *adapted* reading would be to adopt only certain elements of an existing definition: such as "hierarchical constructs...generated via cell driven self organization"**
   Such a reading places emphasis on the organism itself creating a macro material structure. It presents a distinction from organisms which are used to produce ingredients that need further mechanical or chemical processing in order to make a macroscale material.
3. **A single *literal* definition as used by the biomedical[28] field was not found.**

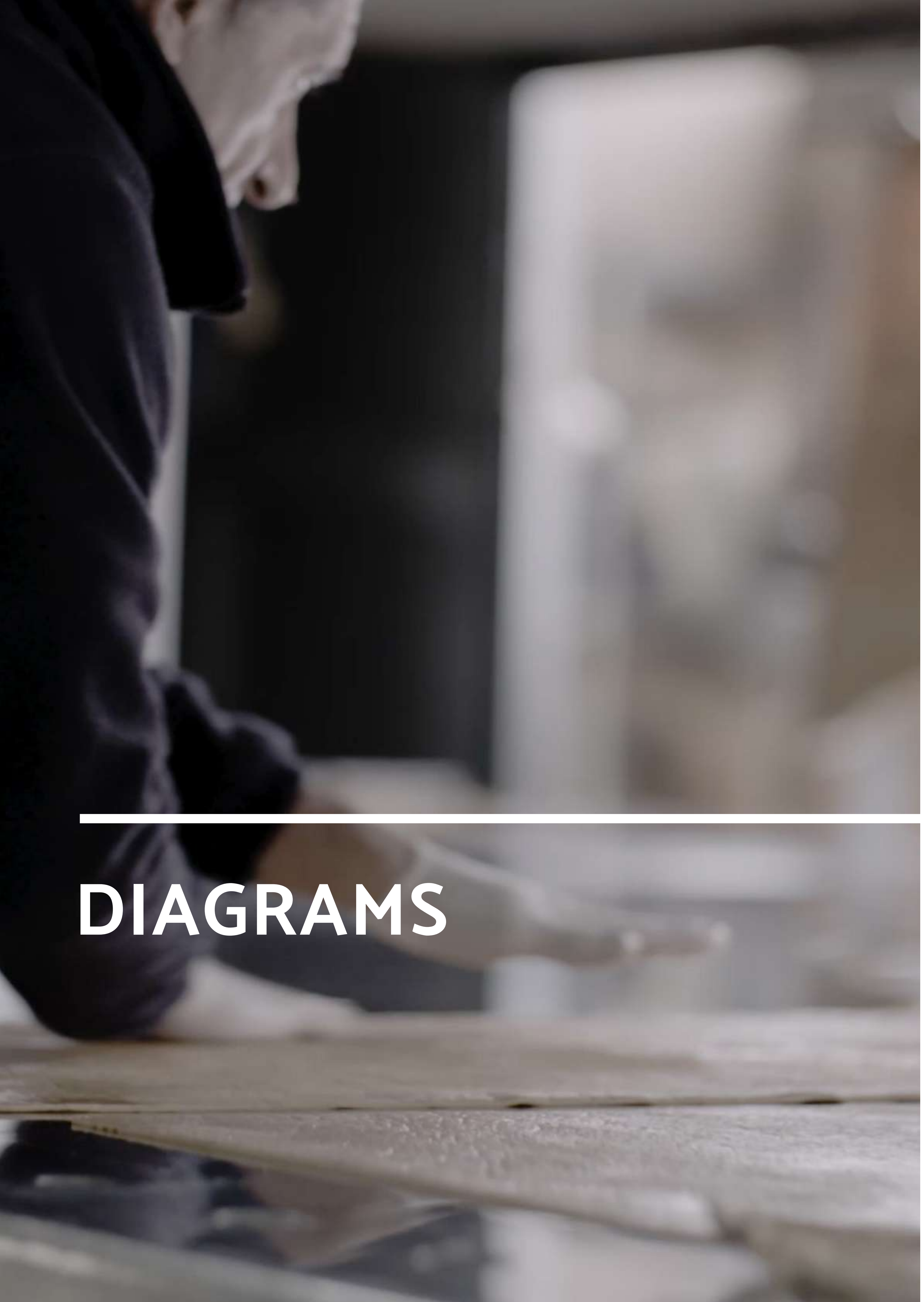
Image: MycoFlex™, Ecovative

SO, WHERE BIOFABRICATION GENERALLY DEPLOYS LIVING ORGANISMS TO FABRICATE THE COMPLEX BUILDING BLOCKS OF MATERIALS, BIOASSEMBLY, AS A SUBSET OF BIOFABRICATION, IS WHEN THOSE **SMALL FABRICATED MOLECULES ARE FURTHER BIOLOGICALLY ASSEMBLED** INTO MICRO OR MACROSCALE STRUCTURES.

This report puts forward the following recommended definition:

Bioassembled:
“A bioassembled material is a macroscale structure that has been grown directly by living microorganisms such as mycelium or bacteria.”

Image: Mylo™, Bolt Threads



DIAGRAMS

WHILST ALL OF THESE PROCESSES MIGHT END IN A MATERIAL DESCRIBED AS A 'BIOMATERIAL', THE **DIAGRAMS SERVE TO HIGHLIGHT** WHAT CAN BE VERY DIFFERENT PROCESSES, INPUTS, OUTPUTS, FEEDSTOCKS ETC.

Image:
L: Courtesy of Made with Reishi™ by MycoWorks

DIAGRAMS

THEY ARE INTENDED TO BE USED AS AN **INDICATIVE SYSTEM** RATHER THAN A COMPLETE LIBRARY OF EVERY CONCEIVABLE PERMUTATION OF MATERIAL PRODUCTION.

INTRODUCTION TO THE DIAGRAMS

To further assist in understanding different 'bio' materials and their manufacture, this section of the report introduces a series of diagrams that lay out the primary production processes. During the conversations and research conducted for the report there were multiple instances when we felt a visual representation would have proven a valuable reference. Our literature review did not uncover any existing comparative resources[29] that span the field of biomaterials. It is our belief that these diagrams are the first cohesive attempt to do so. As a collection they detail how a biobased material differs from the likes of a biofabricated material and so on.

The original intention was to create a couple of illustrative diagrams, but it quickly evolved into a broader series that depicts the main types of 'biomaterial' production processes with more context. They are intended to be used as an indicative system rather than a complete library of every conceivable permutation of material production. An exhaustive set of diagrams would be encyclopedic in length. The goal is that by representing different key production stages it allows a further understanding that text alone would not provide. Our hope is that this is additionally helpful to both brands and innovators alike. By being able to visually contrast one process against another it enables for easier comparative analysis between different technologies and types of materials.

Image: **Modern Meadow**

Whilst all of these processes might end in a material described as a "biomaterial", the diagrams serve to highlight what can be very different processes, inputs, outputs, feedstocks etc.

The diagrams highlight elements such as where a feedstock is employed in a process; what it is, where it potentially comes from, and how it is used. They also show aspects like where a living organism is used for a process such as "biosynthesis", and likely stages where significant environmental impacts might occur.

Finally, it is important to note that it is not possible to represent every single process step, and that these diagrams are intended as a quick start, high level overview. As with any diagramatic portrayal, decisions have to be made as to which steps to represent and which are to be amalgamated. We have aimed to do this with as much parity as possible across processes and material systems. Each diagram is a cradle to gate representation of a material production process. End of use is not detailed in the diagrams, why this is the case is explained later on in this section.

METHODOLOGY

As part of the research phase we reviewed various iconographic representations of processes in this field. Diagrams are used broadly and in varying degrees of detail to describe processes by everyone from large manufacturers[30] and individual startups[31], through to industry non profits[32]. The content of the diagrams in this report was created by reviewing and synthesizing content from said diagrammatic and written depictions of processes where they exist. As each diagram was created to describe a high level process, rather than any individual company's technology, several sources of information were cross referenced for accuracy. Once the first draft diagrams were completed they were sent, where possible, to corresponding experts in their respective fields for feedback and fact checking. The resulting feedback was incorporated into the final diagram layout and contents. Our intention is to further refine them with feedback from scientific experts so they evolve to be constantly accurate and relevant.

DESIGN/ STRUCTURE OF DIAGRAMS

Each diagram in the series captures the cradle to gate process of material production. For example, from feedstock to final material before it is manufactured into a consumer product. Each diagram has 3 key elements; process, inputs and outputs. (For more information on the diagrams structure and how to use them see main key.)

PROCESS

All of the diagrams are designed to be indicative of different types of material production processes, not specific to one company's technology. With each one, the aim is to keep the process steps to the minimum number needed to bring transparency to key stages in production. Each step is represented with an icon. It is important to note that not all companies in this space are responsible for all of these production steps. For example, an innovator may partner with a chemical company who will further convert a chemical into polymer, they may be a supplier to a fabric mill or they may partner with a tannery.

By using the same system and icon set, the diagrams highlight the similarities and differences between various biomaterials and their production processes. Notably, the majority of variations occur towards the start of the processes not at the end. For example, in the case of certain types of "biosynthetics" a microbe (such as a bacteria) may be fed with a sugar source (feedstock) e.g. obtained from corn. The microbe then "biosynthesizes" monomers which are subsequently purified, these monomers are then polymerised and melt spun using the same processes as those in petrochemical based synthetic fiber production. Therefore how the raw ingredients are sourced and produced is different, but the creation of the resulting fiber, yarn and ultimately fabric follow existing manufacturing processes.

Some diagrams involve the convergence of multiple material production streams - only two have been shown here. However, in some cases it could run to more. For example, in the case of a biobased leather alternative, agricultural waste may be mixed with a biobased polyurethane (PU) and a non biobased PU. It's also important to note that any material that has two different material streams converging does not necessarily equate to an equal 50/50 split of one material versus the other in the final material.

Image: **Colorifix**

INPUTS & OUTPUTS

In addition to outlining the major process steps, the diagrams also list principal inputs and outputs. They are designed to broadly capture where impact hotspots may occur, not that every process will have all of the listed inputs and outputs (see key for more information). The diagrams do not capture other material streams such as packaging nor do they include impact hotspots from transportation and shipping. It's important to note that the vast majority of the inputs listed in these diagrams e.g. any chemicals or textiles added, are also manufactured and come from a different and distinct production stream. None of those are represented here as the complexity would be immense.

Having these diagramatic references which reveal where there may be possible inputs and outputs, assists both innovators and brands to ask questions and forge understanding. For example, in instances where there is manufacturing, chemical, or other types of waste it may be that the manufacturer has internal recycling processes for recovering those elements. Therefore whilst the flow of arrows here only suggests movement of resources in one direction, there may in fact be cyclical movement of resources in parts of the process. So a question on this aspect may be; "what are the waste outputs and are they being recovered internally and recycled/ reused?" Or if there is no recovery of resources "what is the waste management procedure to dispose of them?" Alternatively another series of questions could focus on bio content. For example, if a textile is added as a backer a question could be "what does that backer do to the overall bio content of the end material"? If it is a (petrochemical based) synthetic textile e.g. nylon or polyester, it would reduce the overall bio content, if it is a "natural" fiber e.g. cotton, it would contribute to it.

One final key point to make is that there has been no weighting placed on the impact of the inputs and outputs. For example, carbon emissions may be created in the farming of crops but the carbon sequestered during the plant's lifetime may far outweigh these emissions. This is where impact assessments become key, dissecting where the biggest environmental effects occur and working to mitigate these.

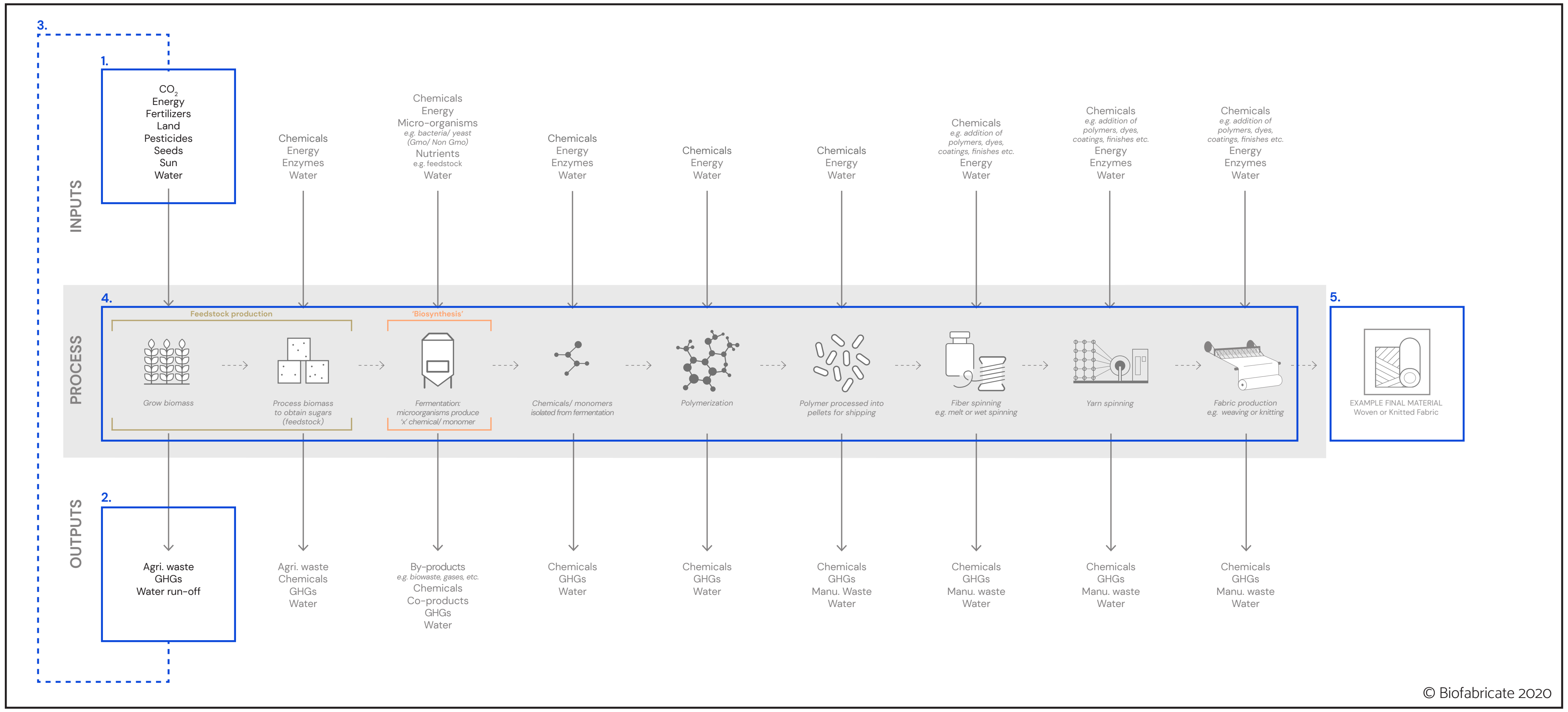
HAVING THESE DIAGRAMATIC REFERENCES WHICH REVEAL WHERE THERE MAY BE POSSIBLE INPUTS AND OUTPUTS, ASSISTS BOTH INNOVATORS AND BRANDS TO **ASK QUESTIONS AND FORGE UNDERSTANDING**.

A NOTE ON END OF USE

This is a topic deserving of its own report. As these diagrams are not specific to any individual company's technologies it is not possible to make generalizations on the end of use of any materials or processes in these examples. End of use is entirely dependent on each specific material's production process and chemistry. For example, some petrochemical polymers are biodegradable and some biobased polymers are not, it is entirely dependent on the chemical composition of each individual material. For further information on this topic please review Ellen MacArthur Foundation's "Vision of a circular economy for fashion"[33] and Fashion for Good's "Polybags in the Fashion Industry" which provide an overview on this topic[34].

Image: **Biosteel®, AMSilk**

NAVIGATION KEY



1.	The lists in these sections of the diagrams detail potential inputs into the different production steps. As all of the diagrams are not specific to one company the elements listed are indicative - each process will have its own specific inputs, and these lists are not exhaustive, or may list inputs not used in some instances. With every process it is important to ask specific questions on what inputs are used at different stages of production.
2.	The lists in these sections of the diagrams detail potential outputs of the different production steps. As with inputs, these lists are indicative.
3.	This dotted line is not included in any of the report diagrams, because they do not represent one company's process specifically. It has been added here to indicate that in many manufacturing processes certain resources are recycled or reused. Where and when this happens is dependent on each individual process/ manufacturer.
4.	These icons represent the primary production steps in the manufacture of different "bio" materials. Underneath each is a short descriptor of what each represents.
5.	At the end of each production process we have included an example final product. In this instance the final product is defined as a material such as a fabric, not a final consumer product such as a garment or handbag.

INPUTS & OUTPUTS KEYS (FOR SELECTED ELEMENTS)

INPUTS	
Energy	This input stands for things such as fuel and electricity
GHGs	Greenhouse gases e.g. carbon oxides and methane

OUTPUTS	
Coproducts	Coproducts are additional valuable products that are created during a production process. In the case of fermentation coproducts can be sold for use in a variety of industries such as for ingredients in cosmetics
Byproducts	At a high level a byproduct is defined as "a secondary or incidental product of a manufacturing process (e.g. scrap or emissions).[35]" In the case of fermentation this may include things like biowaste (e.g. cell debris), gases (e.g. carbon oxides), chemicals (e.g. ethanol).
Chemicals	Chemicals not exhausted in the process, these may be recycled and reused.

1. COMMON MATERIALS PRODUCTION EXAMPLE A: SYNTHETIC

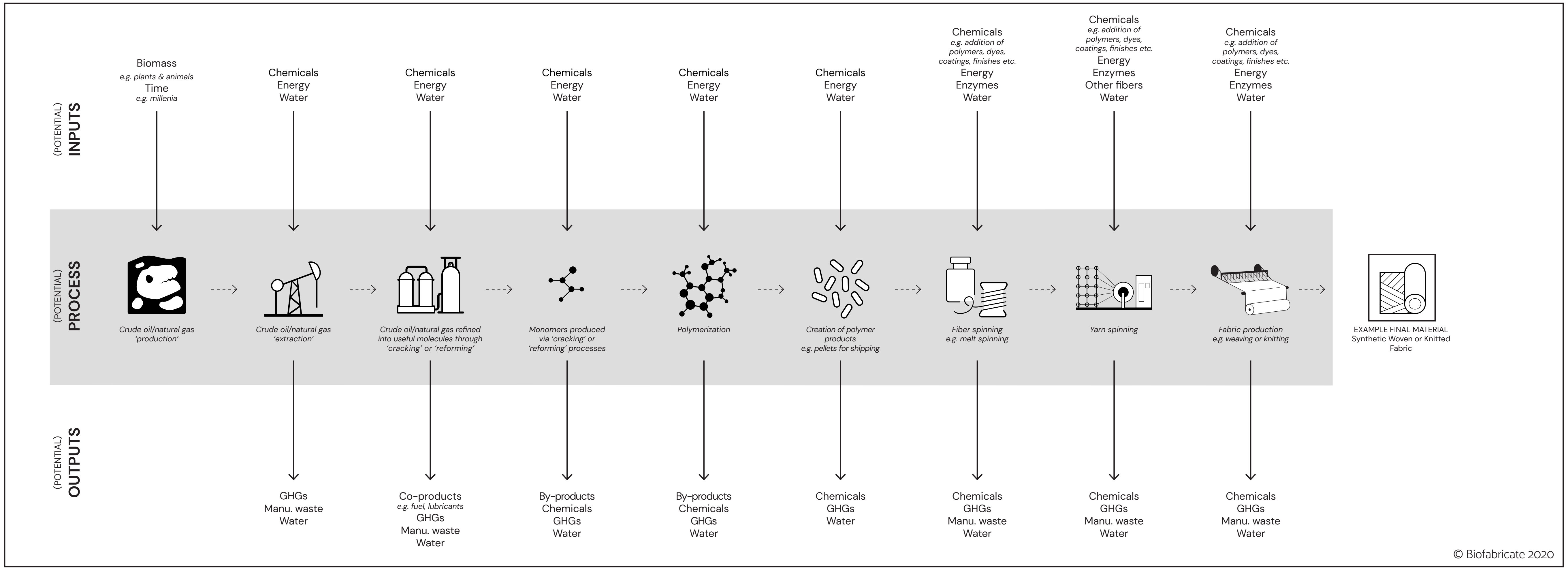


Diagram 1

DIAGRAMS 1 - 3

In creating the diagrams for this section of the report it became apparent that it would be useful to place "biomaterial" production processes into context with three ubiquitous materials used in the fashion industry today: synthetics (e.g. polyester), cotton and leather. It will become clear that parts of their processes are also used in the production processes of some "biomaterials". For example, tanning of mycelium leather or the polymerisation of bioderived monomers which are then melt spun.

As mentioned previously, these diagrams are high level stand ins for processes and as such, some steps may have been amalgamated or not fully broken down. For example, in the case of cotton the separation of the fiber from seeds, burrs and debris is a multi step process, and procedures like dyeing can take place at either the yarn or fabric stage. In the case of leather, many animals are used for their hides and the impacts of rearing of sheep vs pigs or cattle varies, also not all hides are finished e.g. aniline leather. So in all instances we are aware that one size does not perfectly fit all.

As mentioned in the introduction, the arrows in the diagrams are not always indicative of resource movement in only one direction. An example of this is in the production of leather, where, in many tanneries, water is treated and recycled in the process alongside chemicals not exhausted during tanning. Energy may also be created through the gasification from trimmings produced during the tanning process. These types of practices are implemented in many different material production supply chains, and as ever, there are best and worst practices and a sliding scale in between.

Hence the need to ask questions of all aspects of a material's production.

Finally both leather and cotton could be classed as "biobased materials" under the definition put forth by bodies like the USDA. And even a polycotton fabric, with a composition of 75% polyester and 25% cotton, meets the USDA's minimum bio content and can be labelled as a biobased material.

2. COMMON MATERIALS PRODUCTION EXAMPLE B: LEATHER

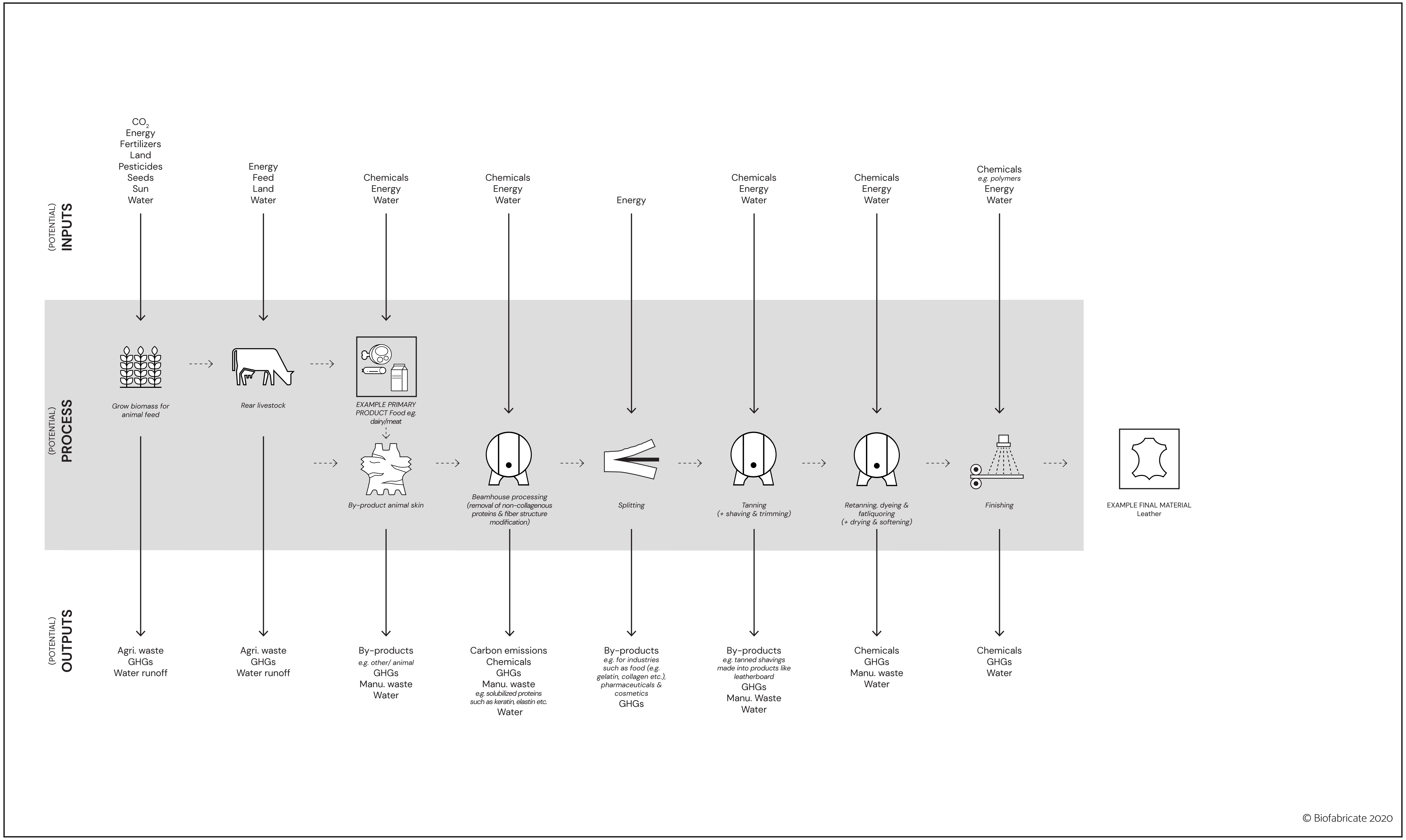


Diagram 2

3. COMMON MATERIALS PRODUCTION EXAMPLE C: COTTON

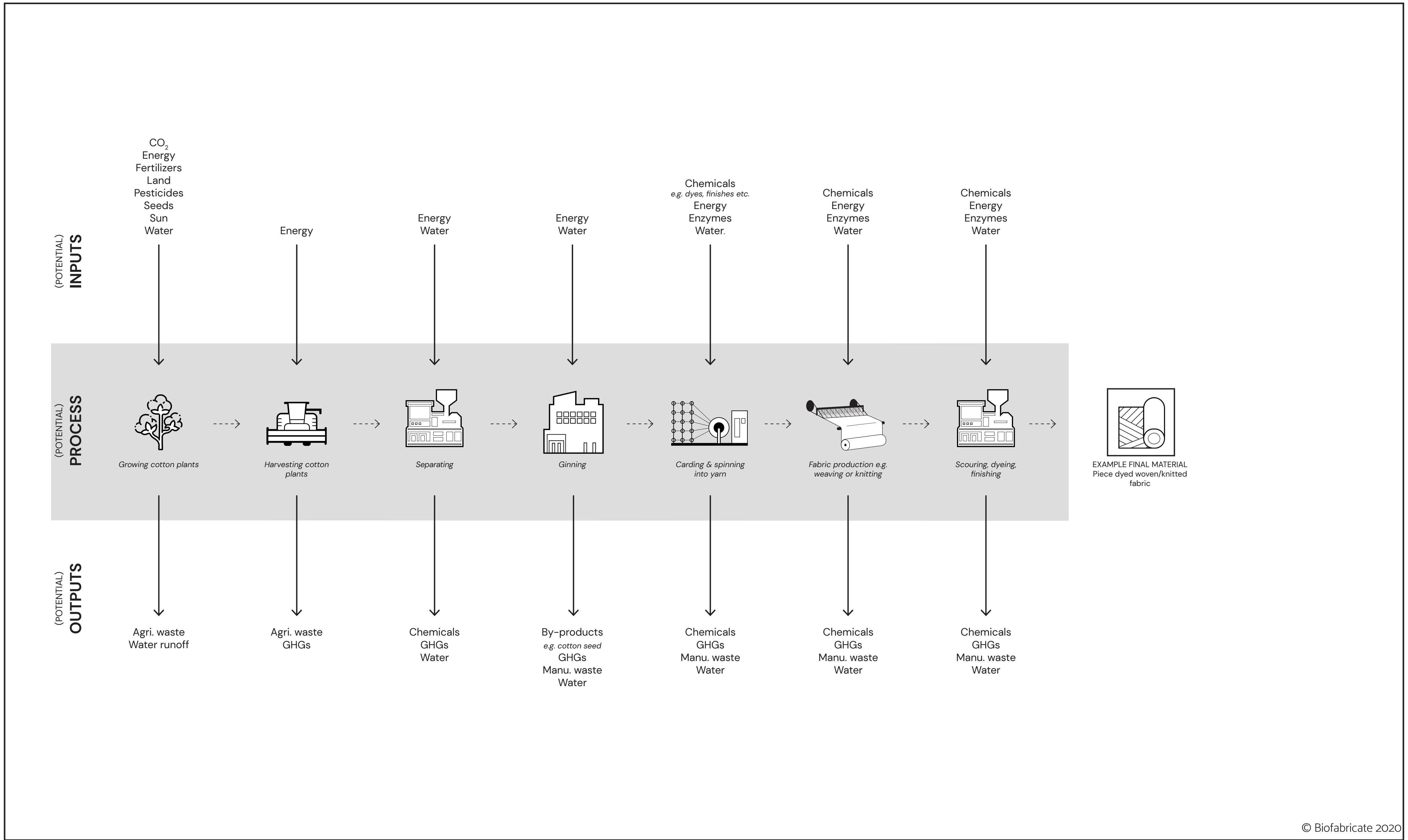


Diagram 3

4. BIOBASED MATERIAL PRODUCTION EXAMPLE A

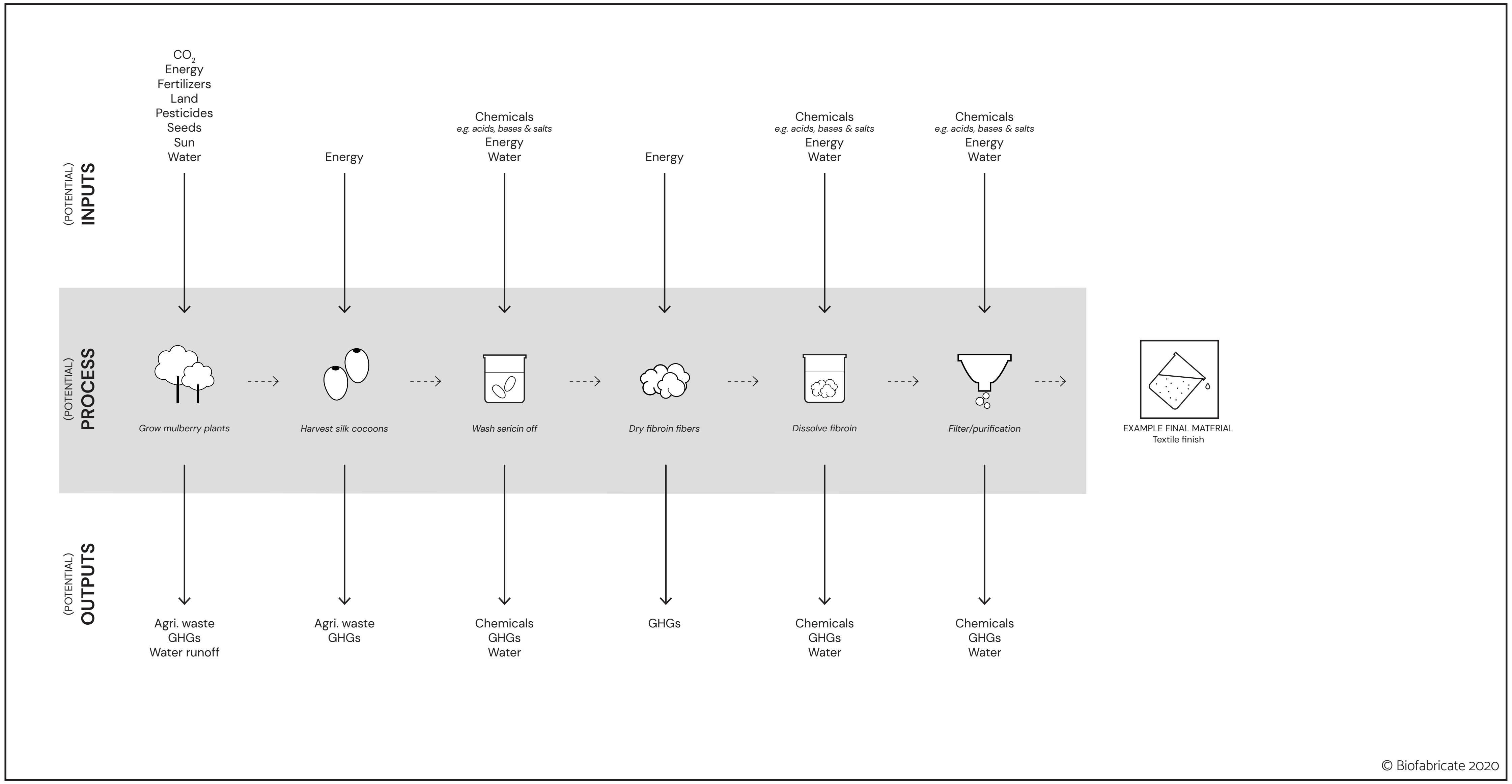


DIAGRAM 4

This diagram shows a very different type of biobased process to diagrams 5 and 6. It lays out a way of processing silk cocoons which is different to the traditional method where the fibers are spun into yarn ("traditional silk" is also a biobased material). This process works with the main silk protein: fibroin. Altering the protein's chemical structure enables various applications such as a textile finish (see diagram 4), ingredients for cosmetics, for medicine or to produce new high performance fibers.

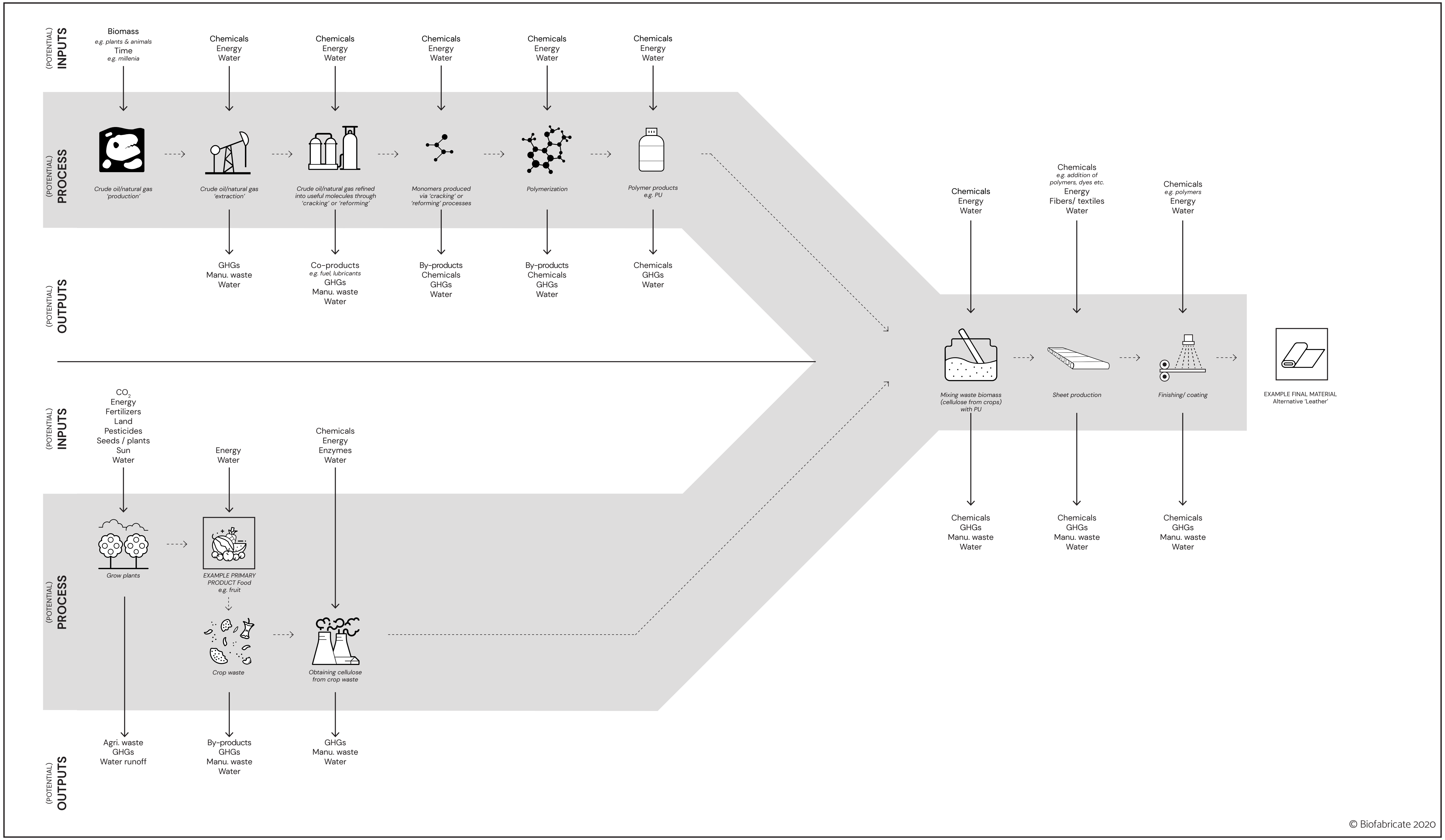
DIAGRAMS 5 & 6

Both of these diagrams show production of some of the newer class of biobased "alternative leathers" that are made from the byproduct of other agricultural processes such as food production. Often, in order to achieve the required performance characteristics, materials of this type are blended with other materials such as PU, as seen in diagram 5. These additional ingredients can be sourced from virgin petrochemical sources or be biobased. The use of a biobased PU would, in most cases, require a three way split diagram, not represented here, as there are no bio PUs made from 100% biomass. Therefore the diagram would show a bifurcation where biomass is grown, chemicals extracted and blended with chemicals from a crude oil source, this would then join with waste cellulose biomass from somewhere like the food industry.

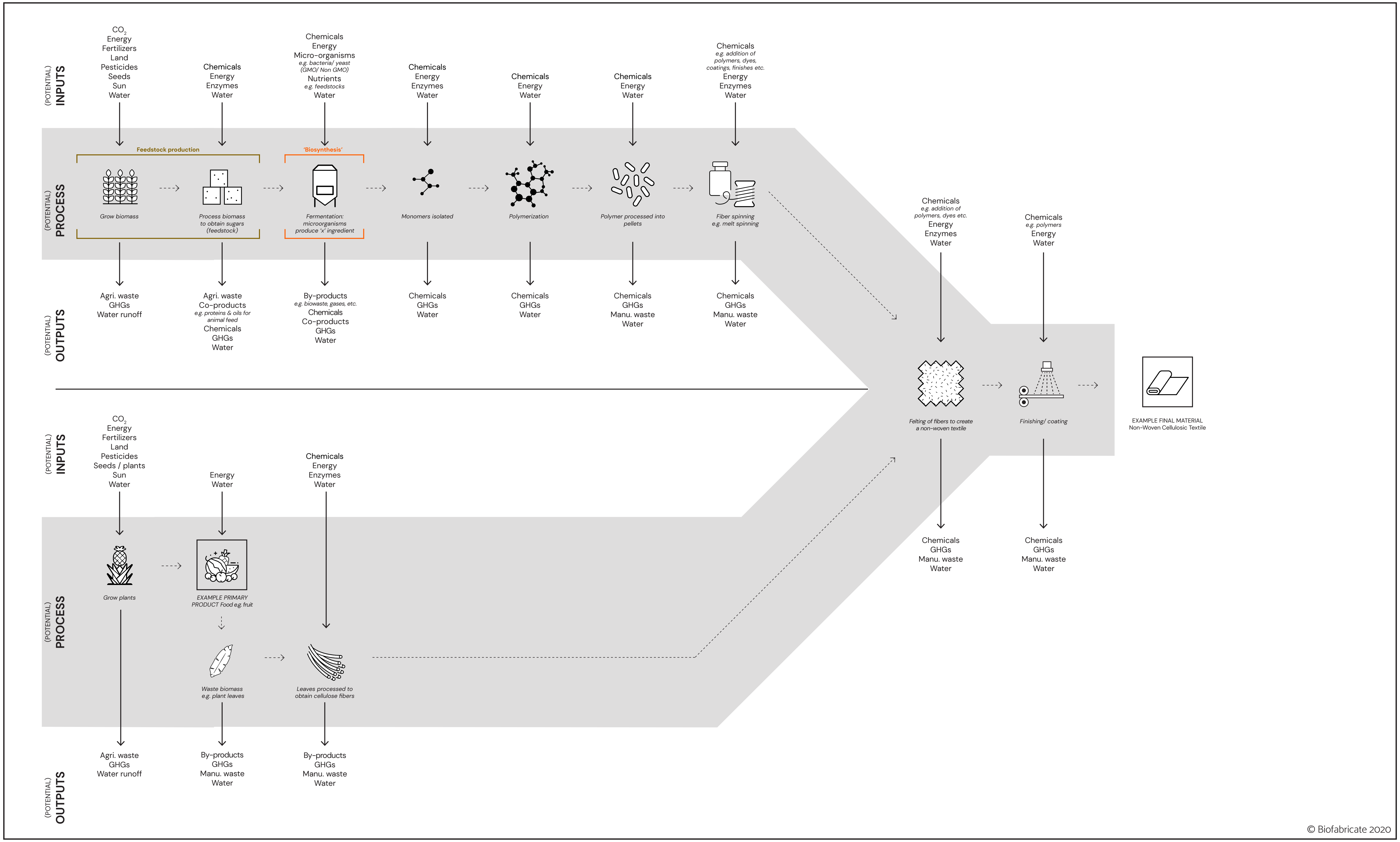
A note on diagram 6; the outputs underneath fermentation list "coproducts". These are secondary products also obtained from the fermentation process. These additional substances can be an important part of a company's economic model. Some coproducts are valued in their own right, for example as ingredients for cosmetics and personal care.

Diagram 4

5. BIOBASED MATERIAL PRODUCTION EXAMPLE B



6. BIOBASED MATERIAL PRODUCTION EXAMPLE C



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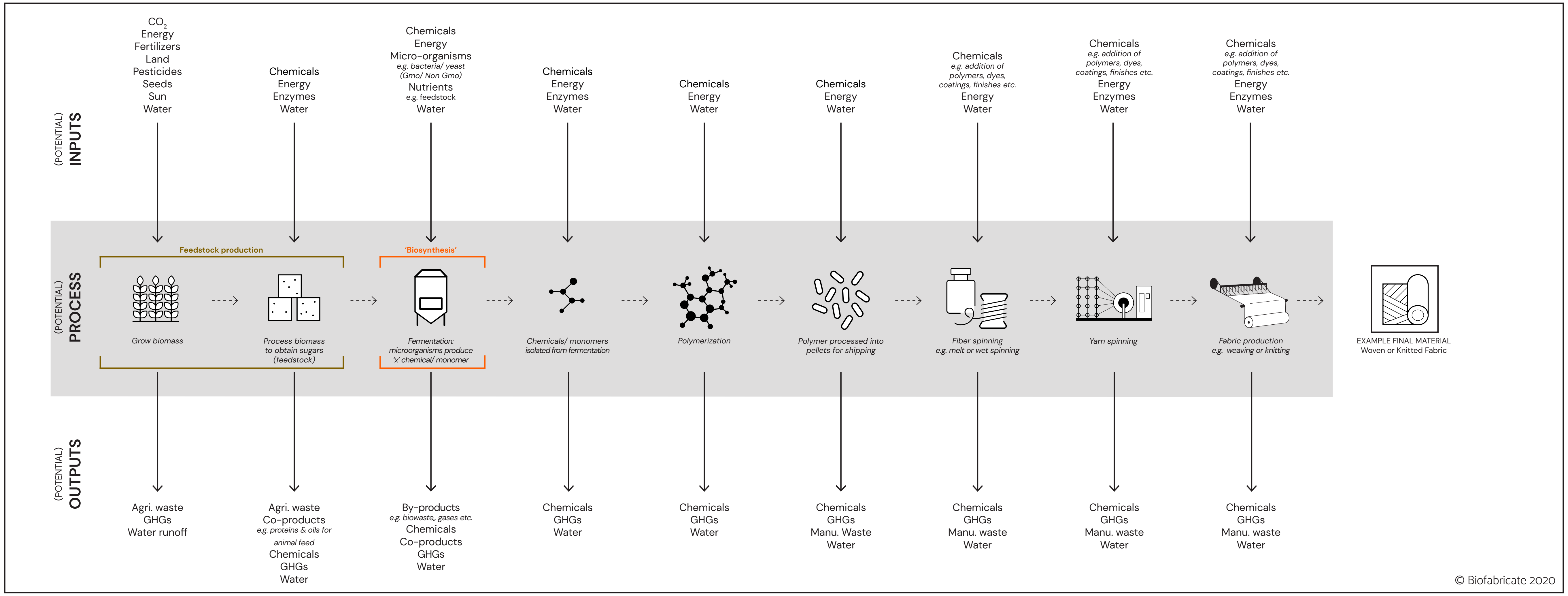
7. BIOSYNTHETIC MATERIAL PRODUCTION EXAMPLE A



DIAGRAMS 7 - 11

As outlined in section 2 of this report, "biosynthetic" is a term which is used to describe a material where either the input is of biological origin, and/or where the process is performed by a living organism (biosynthesis). The first describes a conversion of biomass into something that can be used as a drop in chemical (diagram 9). The second describes a fermentation process which results in a drop in chemical (diagram 7). In this type of process a living organism may additionally be fed with sugars derived from a biological origin. The exception to this rule is a new generation of biotech company who have developed microorganisms that are able to be sustained by greenhouse gases such as carbon oxides or methane as a feedstock instead of sugar (diagram 11). Ultimately, the aim of both routes is to result in an end material that is chemically similar, or identical, to a synthetic derived from a petrochemical source.

The production of these materials is often not as "straightforward" as outlined in diagrams 8, 10 and 11, where the inputs and process solely rely on biology. In many cases the chemicals produced via these processes are combined with chemicals from a petrochemical source (diagram 8). The splits in the diagrams that describe this type of process (diagrams 8 and 10) are not intended to represent an equal division of amounts of material from each production stream. For example DuPont's Sorona[36] comprises 37% polymer derived from renewable sources (via fermentation) and 63% polymer derived from petrochemical sources.

Again as with all the diagrams, because they are not indicative of only one company's process, they stand as high level representations and may not include all steps for all materials. For example, some biosynthetics involve a double, rather than single, fermentation process.

Diagram 7

8. BIOSYNTHETIC MATERIAL PRODUCTION EXAMPLE B

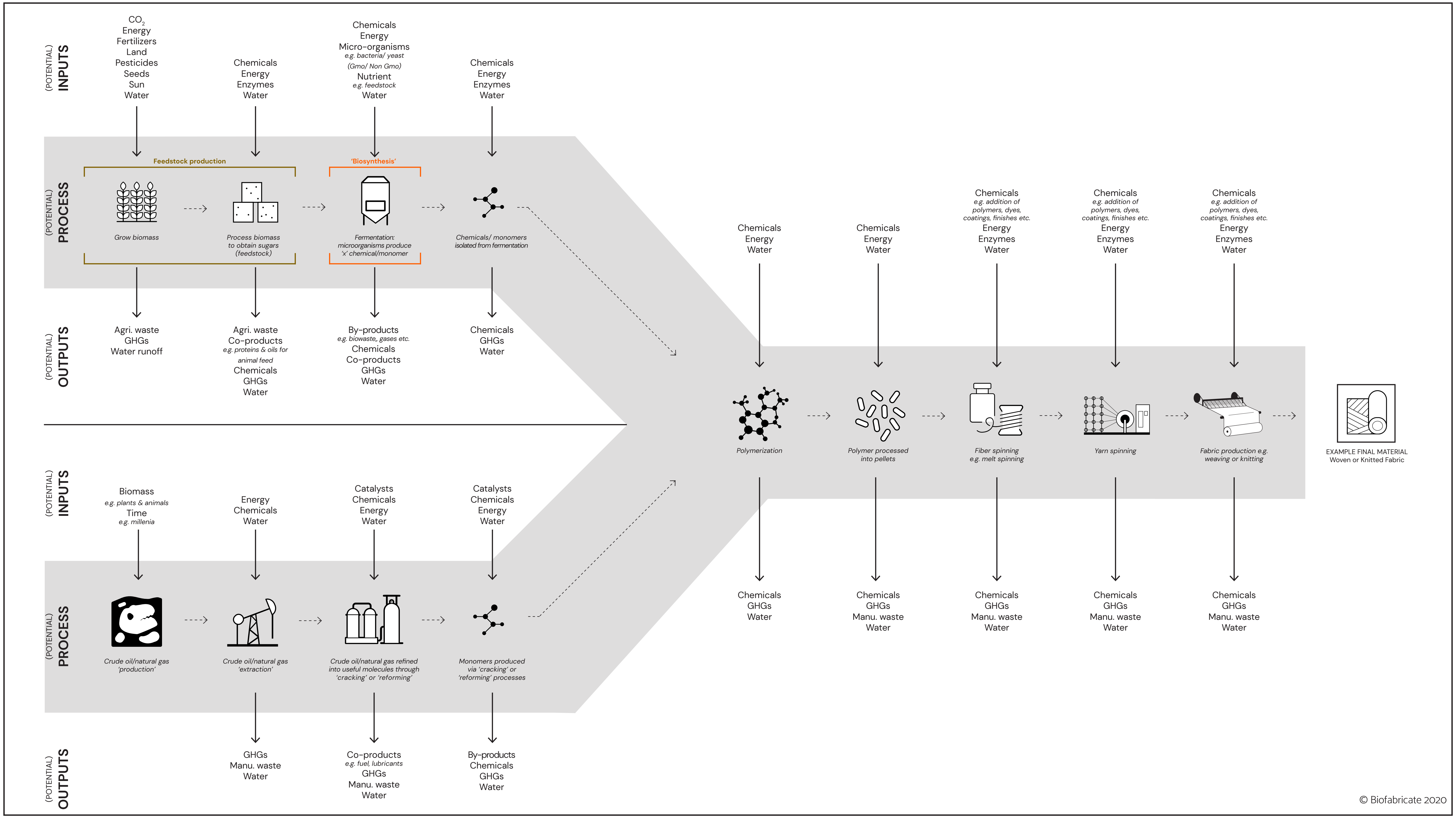


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Diagram 8

9. BIOSYNTHETIC MATERIAL PRODUCTION EXAMPLE C

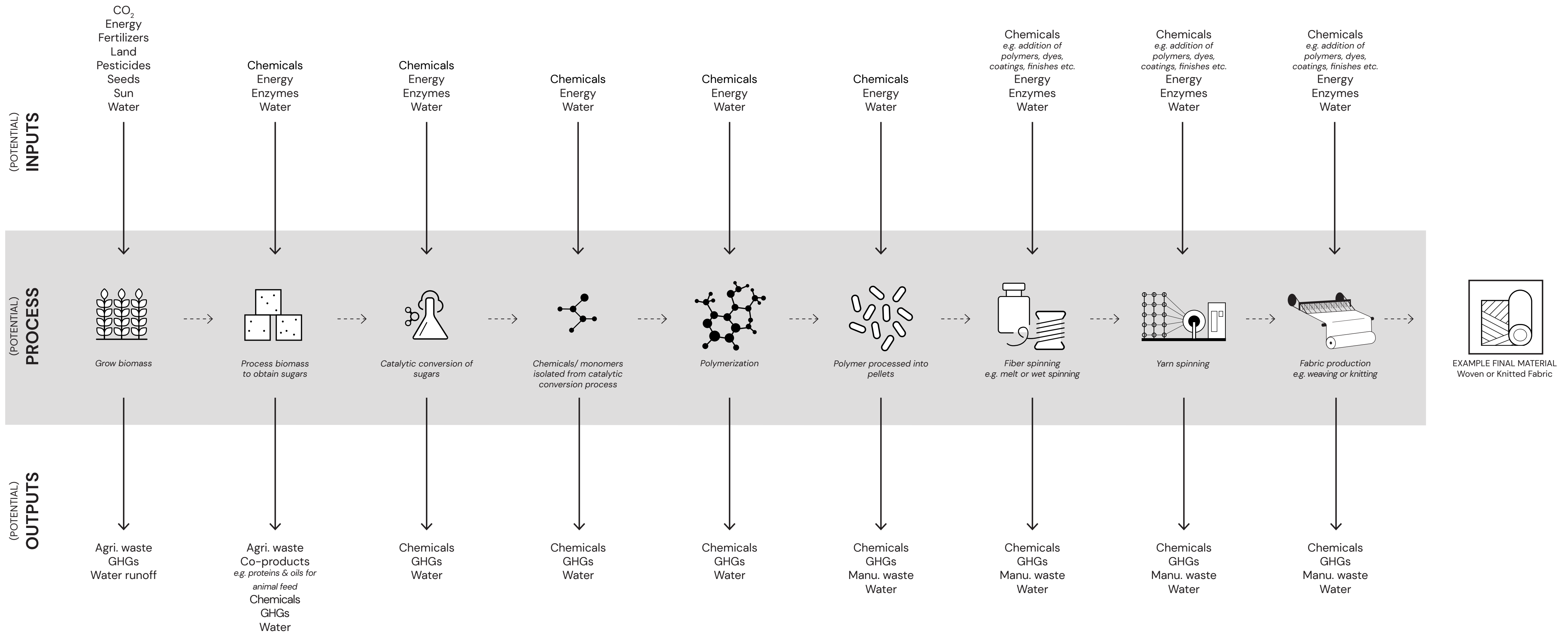

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Diagram 9

10. BIOSYNTHETIC MATERIAL PRODUCTION EXAMPLE D

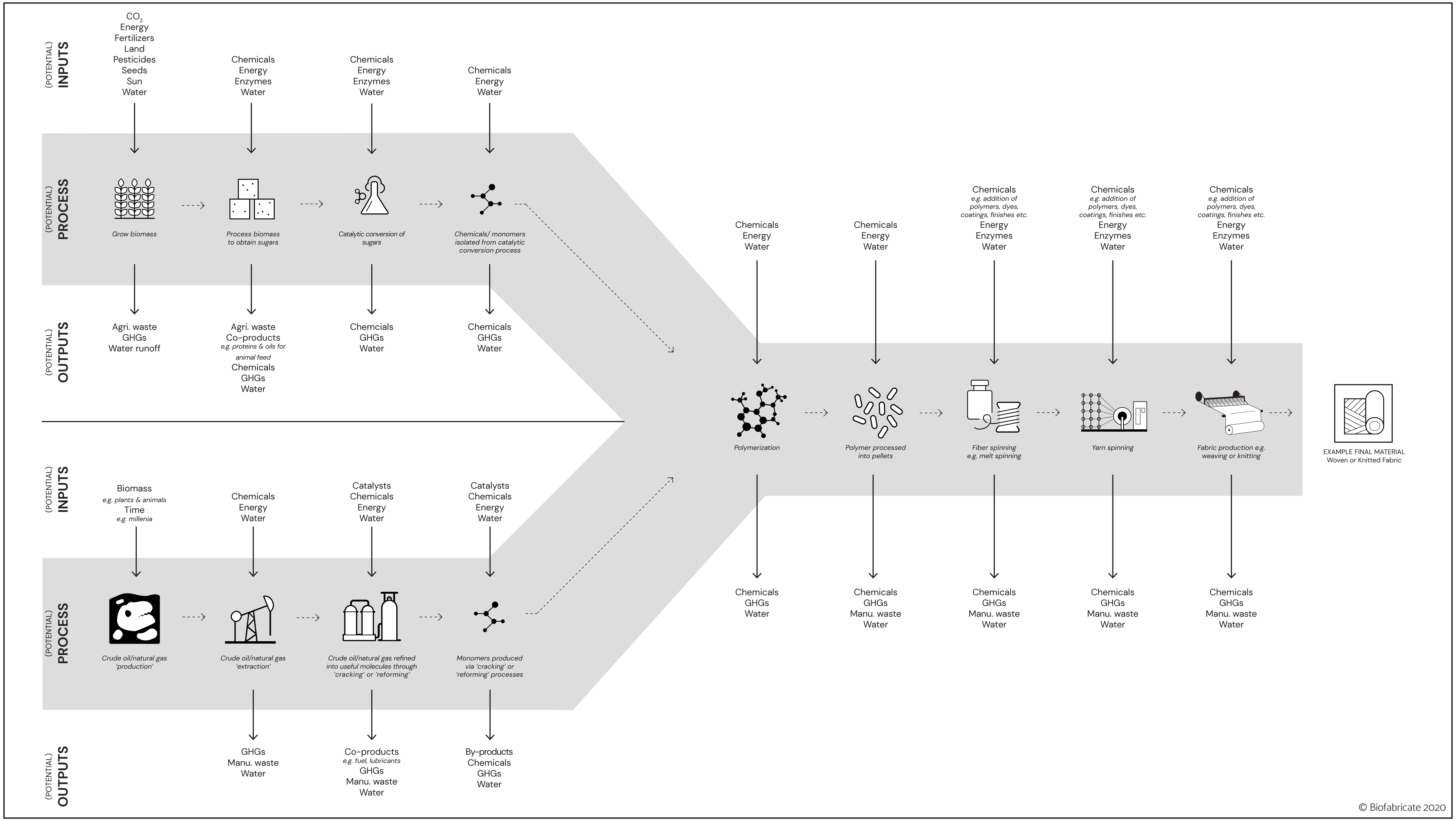

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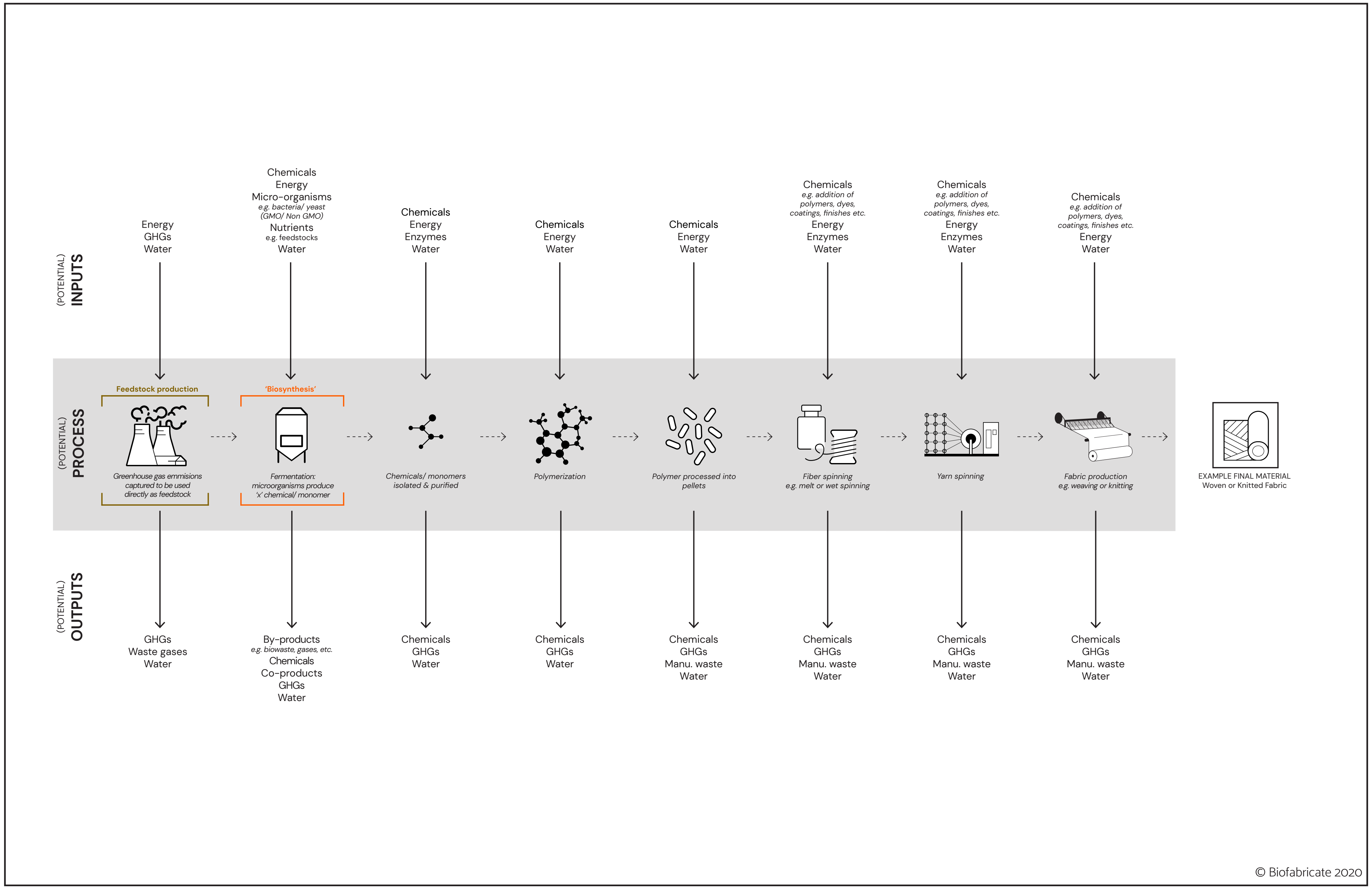
Diagram 10

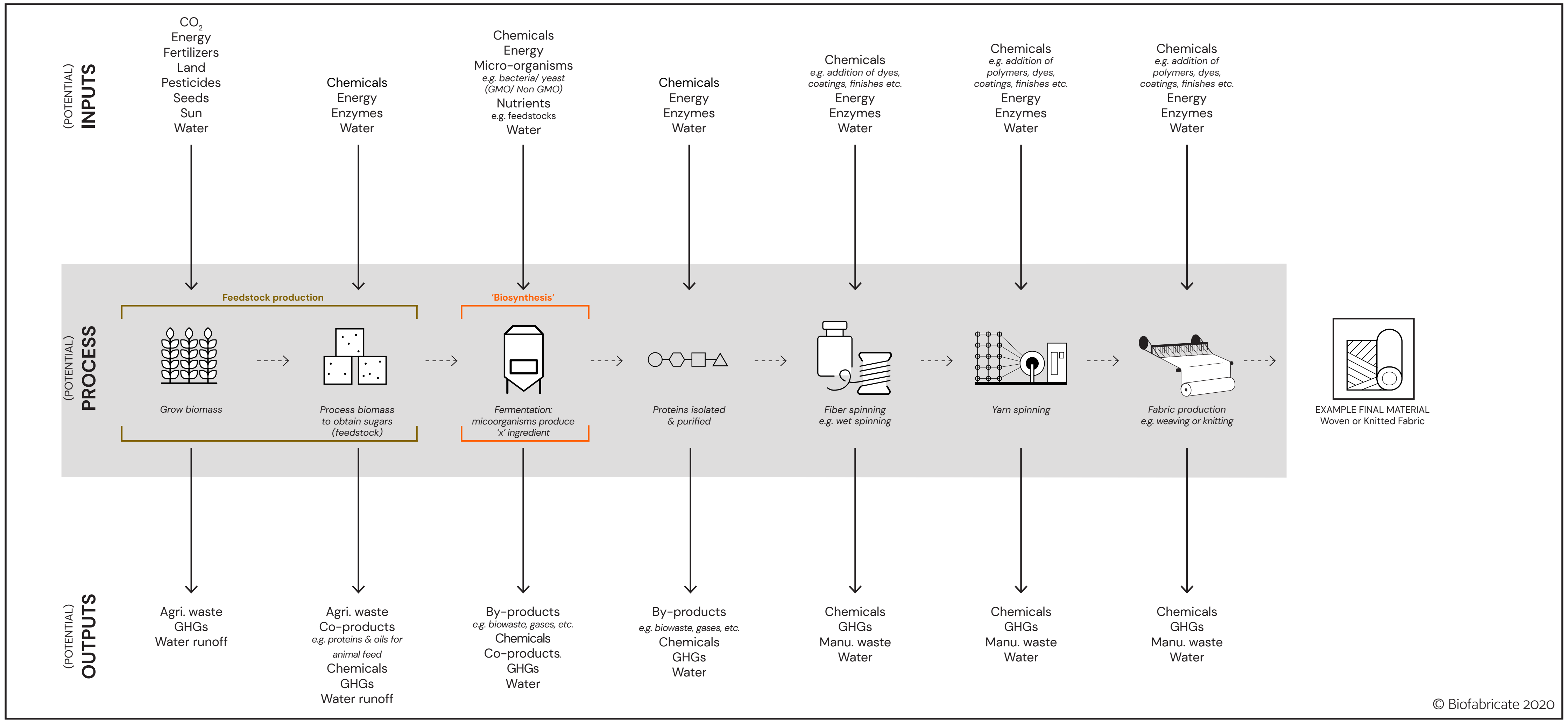
11. BIOSYNTHETIC MATERIAL PRODUCTION EXAMPLE E



THE EXCEPTION TO THIS RULE IS **A NEW GENERATION OF BIOTECH COMPANY WHO HAVE DEVELOPED MICROORGANISMS THAT ARE ABLE TO BE SUSTAINED BY GREENHOUSE GASES** SUCH AS CARBON OXIDES OR METHANE AS A FEEDSTOCK INSTEAD OF SUGAR (DIAGRAM 11). ULTIMATELY, THE AIM OF BOTH ROUTES IS TO RESULT IN AN END MATERIAL THAT IS CHEMICALLY SIMILAR, OR IDENTICAL, TO A SYNTHETIC DERIVED FROM A PETROCHEMICAL SOURCE.

Diagram 11

12. BIOFABRICATED INGREDIENT MATERIAL PRODUCTION EXAMPLE A



DIAGRAMS 12 - 14

These diagrams show a range of technologies that use biofabrication in their production. Specifically, they show technologies that use biofabrication in the creation of "ingredients" which are then further processed, either mechanically, chemically or both into a material such as a yarn or a sheet material. These fermentation based technologies likely harness a microorganism that has been genetically engineered to produce a complex natural building block such as a protein, which is then either spun into a fiber (diagram 12) or formulated into a sheet material (diagram 14). For fibers they can also be blended at a stage in production when this traditionally occurs (diagram 13). Several prototypes and limited edition products have already come to market that have seen protein fibers blended with the likes of either cotton (Spiber x Goldwin Inc & The North Face & Spiber x Sacai), cellulose blends (adidas x Stella McCartney x Bolt Threads) or wool (Bolt Threads x Best Made). Sheet materials may need tanning in order to stabilize the proteins, as with animal leather. Both yarns and sheet materials will likely go through processes such as dyeing and finishing to meet aesthetic and performance requirements.

In contrast to biosynthetics, the aim with many of these technologies is to replicate proteins and carbohydrates found in nature e.g. spider silk and cellulose. Some companies have begun to move beyond molecular mimicry and are exploring how they can become "protein experts" creating novel functionalities not found in nature. For example Japanese biotech company Spiber who have spoken about this in relation to the Moon Parka they developed with Golwin Inc and The North Face Japan (see section 8 for more).

These materials are likely to be made from ingredients produced by genetically modified organisms (GMOs), but do not *contain* GMOs. However, the purification of the proteins must be stringent enough to ensure this is the case. How this is tested, and what the handling procedures are for GMO containing microbial waste, is a key aspect to establish when working with a company innovating these technologies.

Diagram 12

13. BIOFABRICATED INGREDIENT MATERIAL PRODUCTION EXAMPLE B

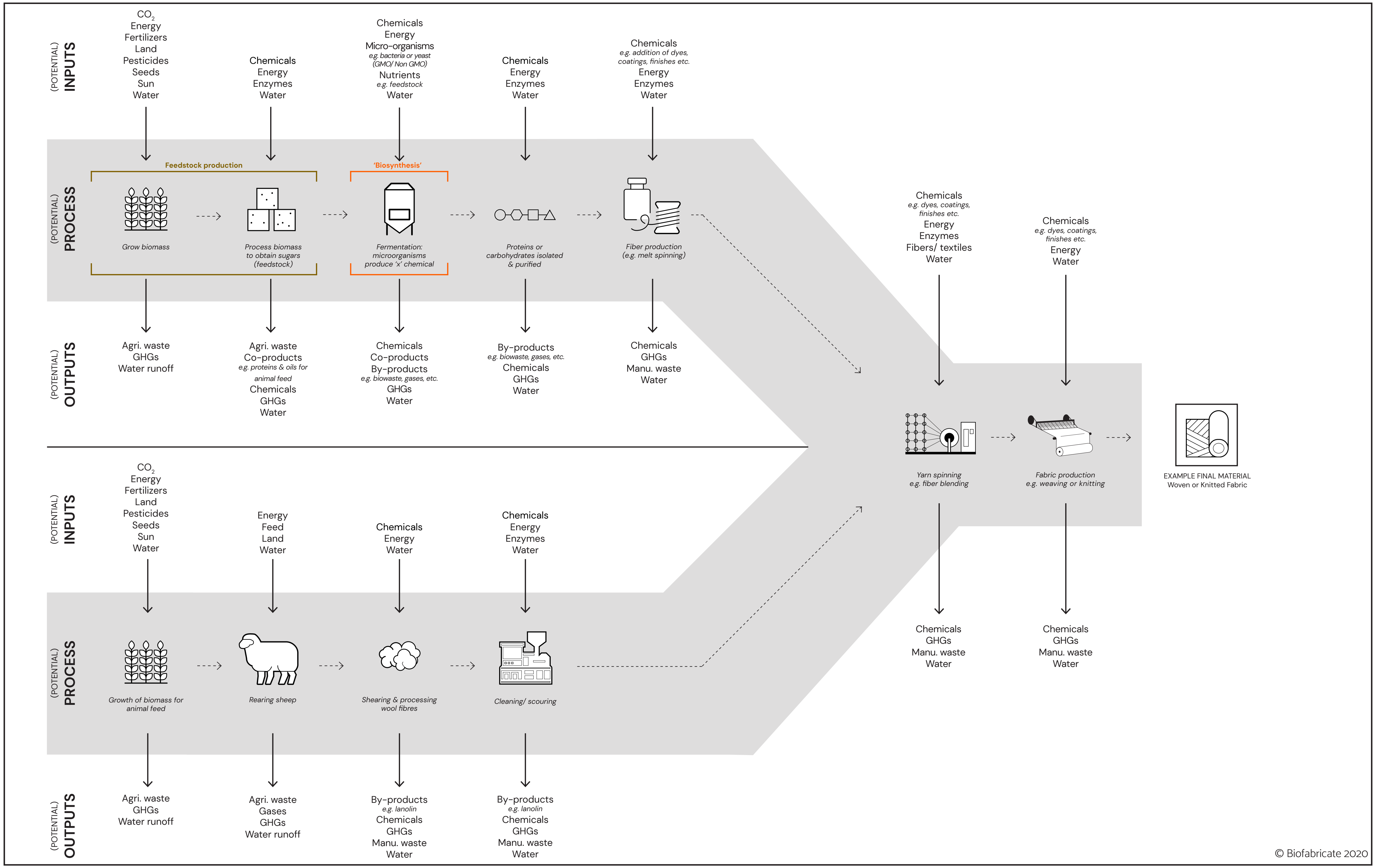


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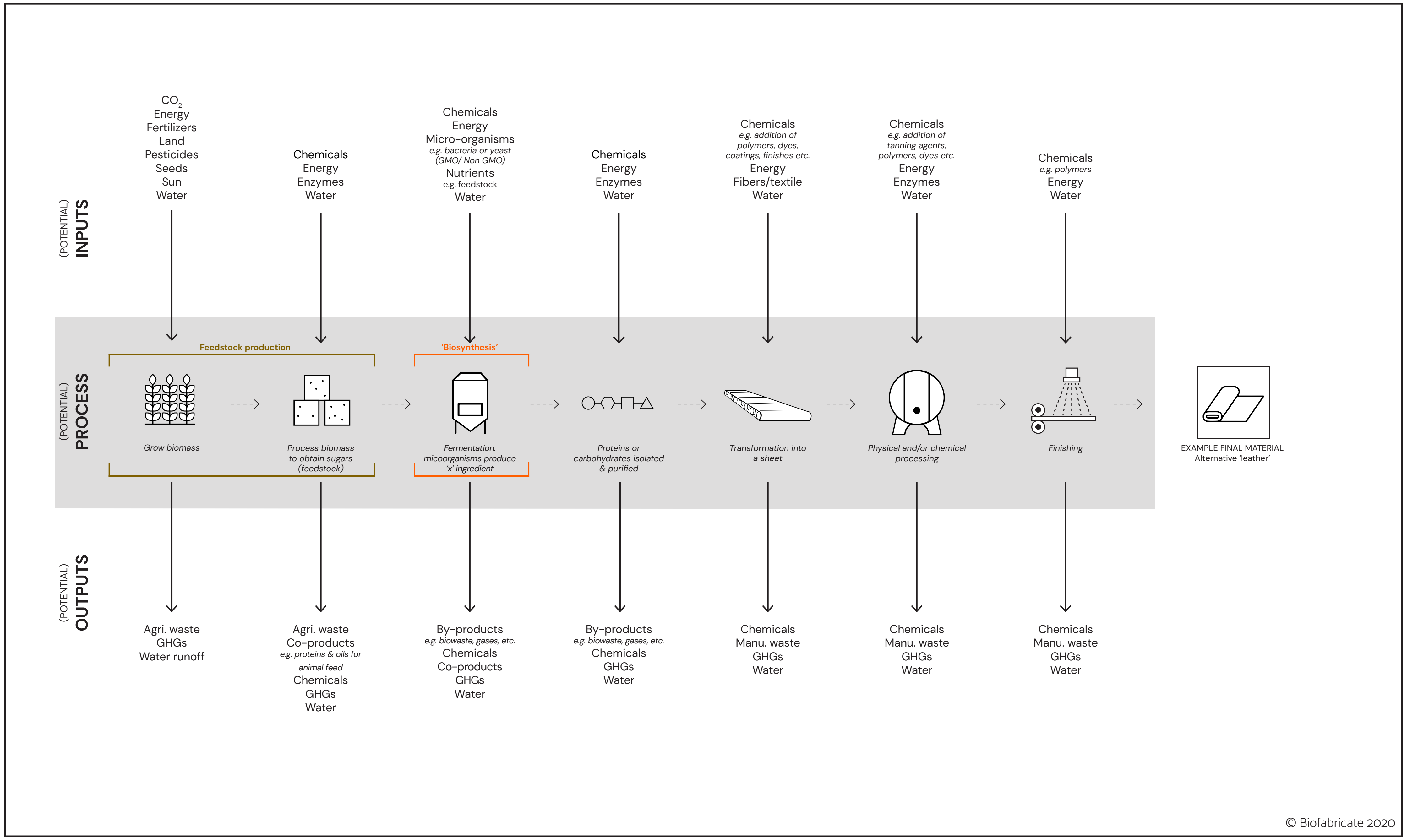
Diagram 13

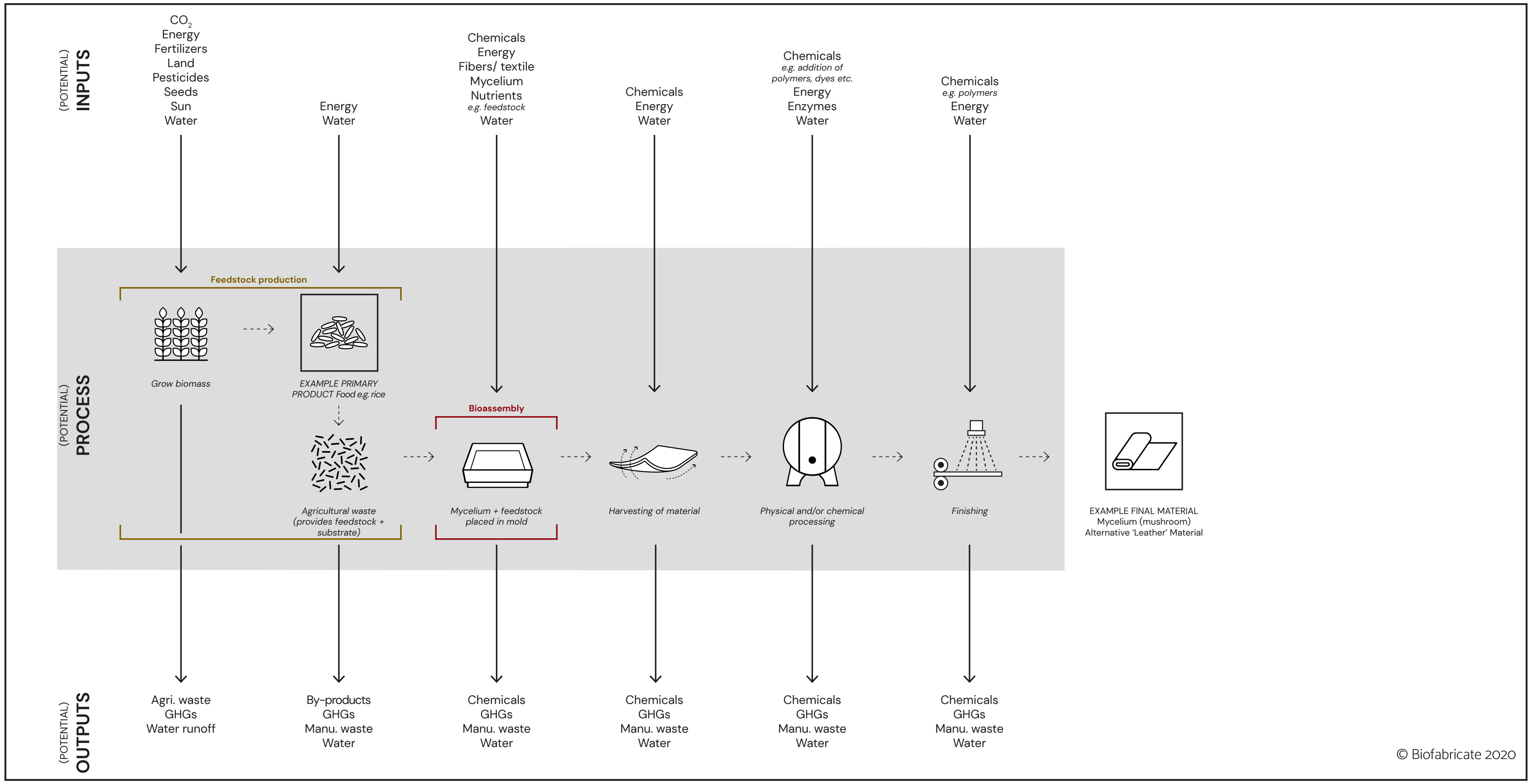
14. BIOFABRICATED INGREDIENT MATERIAL PRODUCTION EXAMPLE C



THESE MATERIALS ARE LIKELY TO BE MADE FROM INGREDIENTS PRODUCED BY GENETICALLY MODIFIED ORGANISMS (GMOs), **BUT DO NOT *CONTAIN* GMOs**.

Diagram 14

15. BIOASSEMBLED MATERIAL PRODUCTION EXAMPLE A



DIAGRAMS 15 - 17

These final three diagrams depict some of the production processes for bioassembled materials. This particular class of material is distinguished by the fact that the organism itself, be that bacteria, mycelium or mammalian cells, assembles the material. They produce a structure that is at the micro/macroscale. At this time, most of these bioassembled materials fall into the loose category of "alternative leather". Perhaps the most well known of this group is "mushroom leather" (diagram 16) which is produced by the root structure of mushrooms called mycelium. The process of growing these materials on cellulosic substrates (often sourced from agricultural waste) most closely resembles indoor farming practices. Once a sheet is harvested it may be subjected to further physical and or chemical processing.

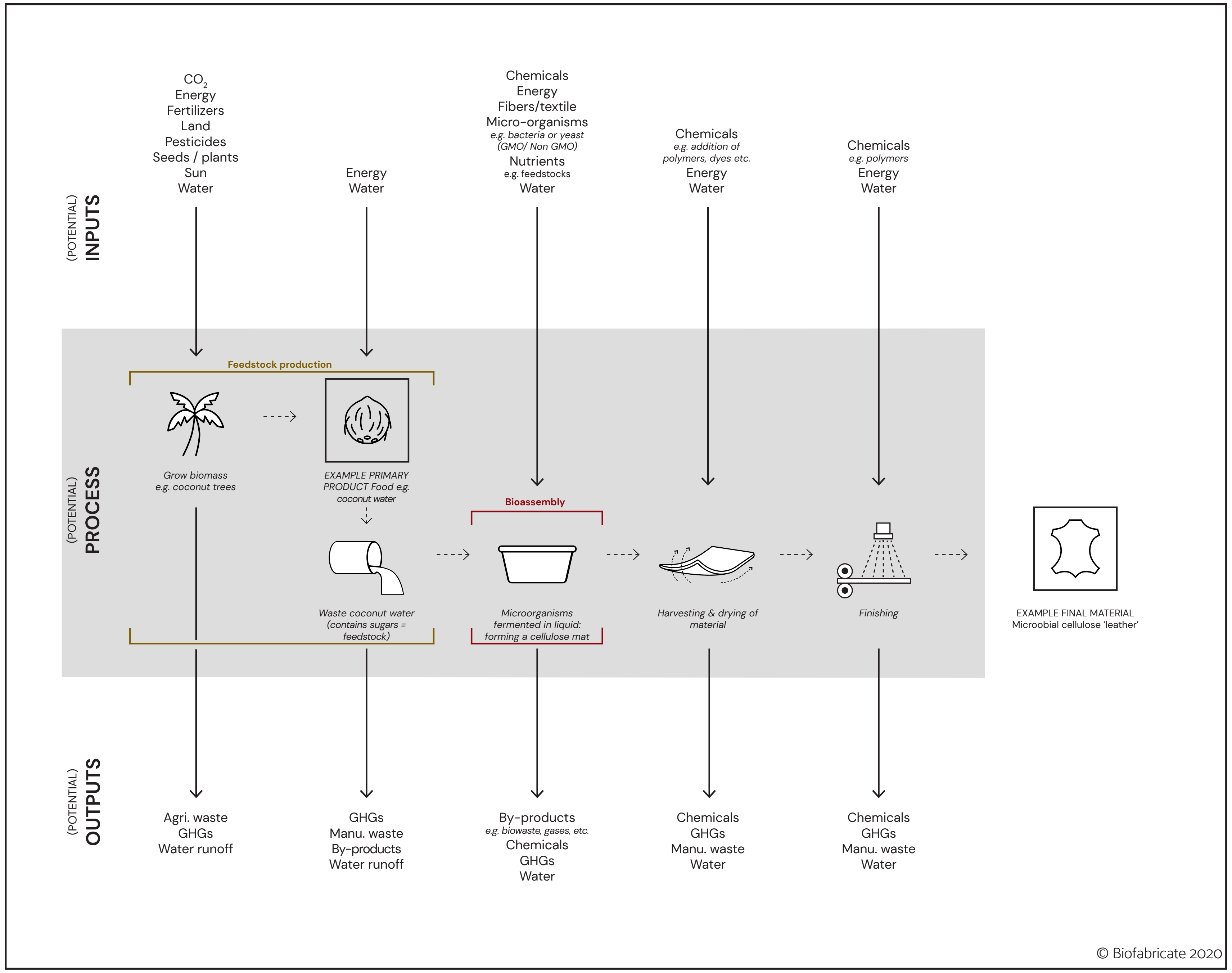
Bioassembly also happens in the production of microbial cellulose (diagram 15). When bacteria and yeast are fed a sugar nutrient source bacteria secrete nanofibers of cellulose which form a mat at the top of the fermentation vat.

The final example given here is the least practiced technology due to its associated costs and difficulty in scaling; tissue engineering (diagram 17). This is where a biopsy of cells is taken from an animal (or cell bank) and grown in vitro (i.e. outside of the body), most commonly, into sheets. Due to the thin nature of the sheets, multiple sheets have to be combined together to achieve a desirable thickness. These materials also need to be tanned and finished to stabilise and fix the material, as with traditional leather. One other key point to raise is that the process of tissue culture is incredibly single use plastic intensive due to the fact that sterility is key to the growth of cells as they have no immune system to prevent infection.

In all these materials a textile or fibers may be added to help support performance of the end product. Finally, it's important to note that although they employ living microorganisms in their production, and in some cases are made of the organism (mycelium and mammalian cells), all growth is terminated before a finished final product is achieved.

Diagram 15

16. BIOASSEMBLED MATERIAL PRODUCTION EXAMPLE B



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BIOASSEMBLY ALSO HAPPENS IN THE PRODUCTION OF MICROBIAL CELLULOSE. WHEN BACTERIA AND YEAST ARE FED A SUGAR NUTRIENT SOURCE **BACTERIA SECRETE NANOFIBERS OF CELLULOSE WHICH FORM A MAT** AT THE TOP OF THE FERMENTATION VAT.

Diagram 16

17. BIOASSEMBLED MATERIAL PRODUCTION EXAMPLE C

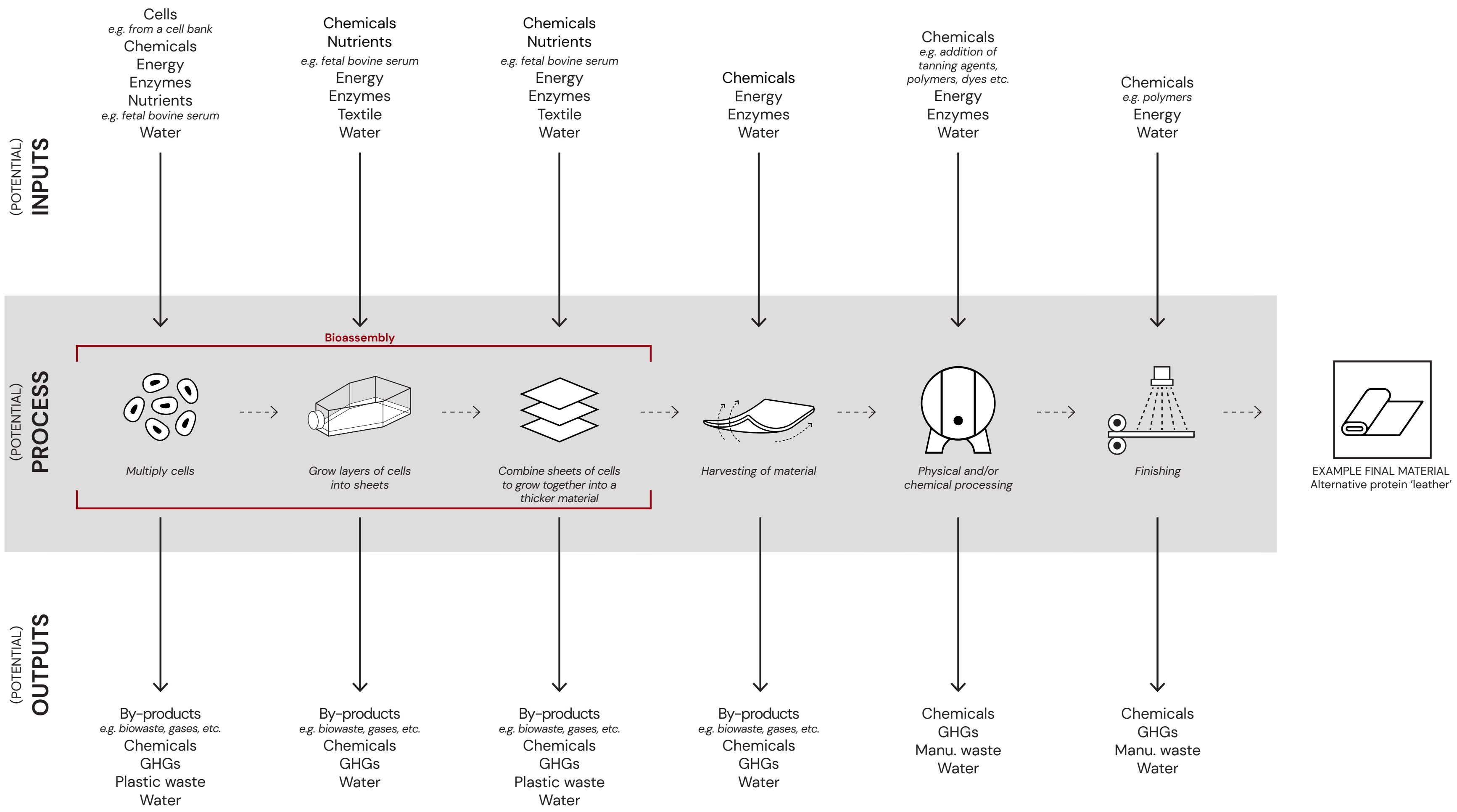

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Diagram 17

THIS IS THE FIRST GENERATION OF COMPANIES ATTEMPTING TO ENGINEER NATURE'S MATERIALS SUCH AS SILK, CELLULOSE AND LEATHER NOT FROM PLANTS OR ANIMALS BUT FROM MICROBES.

Image:
L: Biofabricate Summit 2019, Spiber Brewed Protein™ jacket x Yuima Nakazato, photo by Chloe Hashemi
R: ZOA™, Modern Meadow

ROADMAP TO SCALE

Image:
L: Courtesy of Made with Reishi™ by MycoWorks

This section is focused solely on biofabricated ingredients and materials. These, by their complex nature, take significantly longer to develop and scale compared with, for example, a biomaterial based on mixing readily available biomass with a (PU) binder.

Companies such as AMSilk, Bolt Threads, Ecovative, Modern Meadow, MOGU, MycoWorks or Spiber among others, represent a new generation of consumer material innovation companies that internally combine expertise in both organism design and engineering, fermentation and textiles and materials science - and all the processes in between. Such a coming together of disciplines would previously only have been possible by the likes of a DuPont, DSM, BASF etc.

These new multidisciplinary material startups are built on foundational advances in the tools of biotechnology such as DNA synthesis and Crispr. An acceleration in speed, and drop in price of those tools, has enabled relatively small teams with fewer resources to apply these technologies outside of their traditional realm of application, such as pharma, for consumer materials. This is the first generation of companies attempting to engineer nature's materials such as silk, cellulose and leather not from plants or animals but from microbes.

CONTRARY TO THE SENSE ONE MIGHT GET FROM MEDIA REPORTS, **ONLY ONE OR TWO BIOFABRICATED TEXTILE PRODUCTS ARE ON THE MARKET IN 2020.** ONE EXAMPLE IS GERMAN COMPANY AMSILK'S BIOFABRICATED WATCH-STRAP WITH LUXURY BRAND OMEGA (LAUNCHED IN 2018)

It is still just the dawn of a material revolution that will unfold over the coming decades. The promise of these technologies is that designed biology allows access to all the benefits of nature's performance, aesthetics and comfort and beyond, but without the same environmental footprint.

Contrary to the sense one might get from media reports, only one or two biofabricated textile products are on the market in 2020. One example is German company AMSilk's biofabricated watch-strap with luxury brand Omega[37] (launched in 2018), while Japanese company Spiber has also released a limited edition series of jackets in collaboration with The North Face[38] (launched in 2019) as well as couture collections with designer Yuima Nakazato[39] and t shirts with sacai[40] (also 2019).

The vast majority of material innovators are still in development stages Technology Readiness Level (TRL) 4 to 7 (see section 4 on scaling technologies). Technology Readiness Level is a type of measurement system used to assess the maturity level of a particular technology[41]. While all entrepreneurs seek to get to market fast, the reality of scaling these complex technologies is that they take time and many "bumps" are likely to be encountered along the way. From designing and engineering cells to produce novel proteins, scaling organisms that will be stable as they go into large fermentation facilities, purifying proteins so they can be spun into fibers or formulated into materials; each process requires specialized expertise and equipment. One or more processes may be novel, and their scale up path may not always be obvious or a given for less experienced innovators. Some companies may choose to partner strategically to expedite certain stages, but even so technology transfer can take months to years.

The difficulty in transitioning a new technology from pilot or demo scale, to being able to supply consistent quality and volume for running on a commercial manufacturing line is often referred to as the "valley of death". Factors affecting scalability also include access to sufficient capital, affordability, reliability, supportability and so on. Arguably none of the biofabricated material innovation companies today have yet bridged that gap though a few are about to attempt to do so.

Both Spiber and AMSilk were founded over a decade ago; 2007 and 2008 respectively - an indication of the true length of time it takes to bring a biofabricated material to market. Neither company are producing commercial volumes at global scale yet, though Spiber's

Images:
R: AMSilk/ OMEGA NATO Biosteel® strap
L: Spiber, Brewed Protein™ and cotton blend T-shirt by sacai

WHILE JAPANESE COMPANY SPIBER HAS ALSO RELEASED A LIMITED EDITION SERIES OF JACKETS IN COLLABORATION WITH THE NORTH FACE (LAUNCHED IN 2019) AS WELL AS COUTURE COLLECTIONS WITH DESIGNER **YUIMA NAKAZATO** AND T SHIRTS WITH **SACAI** (ALSO 2019).

first commercial scale plant is due to come online in 2021[42] and AMSilk are on track to scale production for a major brand partner launch in 2021. Spiber has additionally recently announced an agreement with Archer Daniels Midland (ADM) to expand the production of their Brewed Protein™ polymers.[43] Bolt Threads plan to launch products made of Mylo™ with their consortium of brand partners[44] in 2021 while MycoWorks, having debuted Reishi™ in February 2020, are also set to announce brand partners[45] this year.

"IN THE CASE WITH MYCOWORKS, I HAD ALREADY BEEN WORKING WITH MYCELIUM. IT WAS A MEDIUM THAT I WAS FAMILIAR WITH FOR A GOOD 15 YEARS, AND THE PROOF OF CONCEPT OR **THE PROTOTYPE EMERGED FROM AN ALREADY ESTABLISHED PRACTICE."**

PHIL ROSS, CTO & CO-FOUNDER, MYCOWORKS

R&D

RESEARCH & DEVELOPMENT (R&D) TIMELINES

The timelines involved in developing materials using the toolkit of biotechnology are long and complicated, which is at odds with an industry such as fashion that moves at breakneck speed. These timelines are measured in years, not months, with many of the innovators interviewed quoting an average of 5 plus years for R&D. The reality can often be longer, for example in the case of Japanese biotech Spiber who launched their first prototype with The North Face Japan in 2015, representing a timeline of 8 years followed by an additional 4 years on material R&D. We dive into the reasons why and the issues encountered further on in this section.

For many of the companies in this space, they are also building their technology on fundamental work done by founders as part of Ph.D. research, programmes which average 8 years[46] of study in the sciences. For example, Huue's technology (formerly Tinctorium) is based on the 4 years of doctoral work by its co founder and Chief Scientific Officer Dr. Tammy Hsu conducted whilst at UC Berkeley. Bolt Threads Microsilk™ platform grew out of the Ph.D. work of its founders whilst studying at UC San Francisco and UC Berkeley. A further case of extensive work done prior to the formation of a company is that of Phil Ross, MycoWork's co founder and CTO, who had been researching and experimenting with mycelium in his artistic practice for almost 20 years before the startup was founded.

"In the case with MycoWorks, I had already been working with mycelium. It was a medium that I was familiar with for a good 15 years, and the proof of concept or the prototype emerged from an already established practice."

What is clear from these examples is that company founding dates do not always encompass the true time it takes to develop these types of technologies and materials.

STAGES OF R&D

Startups in this space are often the equivalent of several companies in one, comprising teams specialising in disciplines such as cell engineering and fermentation, through to material science and textile manufacture. Each department needs to play their role effectively, and these elements need to be brought together into a system that is scalable at a viable cost. Charles Dimmler, CEO of Checkerspot, explains how Checkerspot's technology platform rests on three functional areas:

"One is what we refer to as a molecular foundry, and that's where we're working with microbes to produce these molecular building blocks. The second is material science; chemistry to assemble those building blocks into materials and have high-performance features. And then third is fabrication. And so that has an obvious link to biofabricated."

The road to achieve this is not a linear one and is often iterative as technologies mature. Outlined below are the main areas of research undertaken by innovators in developing their materials.

ORGANISM SELECTION & ENGINEERING

The timelines spoken to above also reflect the fact that, no matter how much more "programmable" biology has become, these technologies employ the use of living organisms in their production and this brings its own unique set of challenges.

The majority of the companies using microorganisms like bacteria, yeast and algae, to synthesize things like proteins have had to engineer those organisms with the desired functionality. For example, in the case of innovators creating fermented spider silks', their cell engineers needed to identify the gene sequences responsible for producing silk in spiders and then insert this code into the genome of a microorganism like a yeast or bacterium. Large numbers of slight variations in gene sequence are cultured and screened in order to find a promising strain that produces the required protein in sufficient quantity and quality. The most successful strains are then run in small fermentation trials to ensure that the organisms perform as expected in a scaled up environment.

In the case of companies working with fungi, it is more likely that they will screen different strains of mycelium found in nature to select the most promising one for the application.

FERMENTATION & PURIFICATION

For technologies based on microorganisms such as bacteria and yeast, when a promising strain has been identified its fermentation conditions need to be further refined - including the optimum pH value and nutrition (amount and type of feedstock). This allows for the identification of the best conditions for growth and to support the production of the largest quantity of the desired substance e.g. protein. The product yield is usually referred to as the "titer".

Organisms that biofabricate complex proteins such as silk or collagen are unlikely to be secreting the protein. Instead, further processing is needed to obtain purified material. Often referred to as DSP (downstream processing), cells are broken apart (known as lysing), and then a series of steps separate the protein from other materials e.g. cell debris. This stage usually needs further research in order to refine the purification.

People most frequently associate fermentation with beer or wine: large stainless steel tanks full of liquid and microscopic organisms brewing alcohol. The growth of mycelium however is also referred to as a fermentation process, most commonly "solid state fermentation" where the mycelial cells are grown in a mold on a substrate. This substrate is a mix of nutrients (including a feedstock such as dextrose) and non nutrients (e.g. an agricultural byproduct such as hemp hurd). The same need exists to identify optimum growth conditions; including temperature, humidity, air flow, nutrient type and amount etc.

MATERIAL CREATION & PROOF OF CONCEPT

Microbial proteins such as silk and collagen require further processing in order to be made into yarn or sheet materials. This is achieved by either mechanical or chemical means, or both combined. For example, wet spinning a protein into a fiber and then spinning this into a yarn. Materials may also need additional processing in order to be fit for use, such as tanning and finishing in the case of mycelium leather.

Early materials made by innovators can look incredibly convincing and the creation of initial proof of concept prototypes can happen relatively quickly. However, more often than not, there is no test data on the material itself, let alone in application. This can give the appearance that a company is further ahead, when the reality is that once a proof of concept has been achieved this is where the real work often begins not ends.

An example that was shared at the Biofabricate summit in London 2019 was the collaboration between Spiber , Goldwin Inc and The North Face Japan. In 2015 they showed a prototype jacket which looked ready to be sent down a mountain on the back of a pro skier. According to Director, Kenji Higashi, of Spiber, what actually followed was an additional 4 years of further development between the two teams: "trying to figure out how to use our materials in a garment, and it took a lot of technical resources, not only from Spiber but also from The North Face". The further work was to make a material that met the strenuous standards of performance sport, but the most pressing issue to solve occurred when the material got wet, when it would shrink by several tens of percentage points. A phenomenon known as "super contraction", and a key feature of spider's webs, it was not ideal for a performance garment. The first attempts to solve the problem involved preshrinking the material and coatings. However, "within a year after starting to develop the Moon Parka we decided that we needed to go back to the drawing board, go back and redesign the amino acid sequence of the protein, use what we learned from nature, and design a new protein that won't shrink as much as spider silk".[47]

Whilst continuing to develop their materials, Spiber also collaborated with Japanese couturier Yuima Nakazato for his AW 2019 and SS 2020 collections. This strategy allowed for experimentation but in a controlled way, where the amount of material needed is highly limited. Many of the garments incorporating Spiber's Brewed Protein™ fabrics explored a technique developed by the designer called "Biosmocking" which "works by precisely controlling the super contraction property of specially-tailored Brewed Protein™ textiles".[48] This collaboration allowed for a creative exploration of the limitations of a material in development. This example highlights the complexity of developing these types of materials: even when you are able to produce a yarn there can be years of iterative development cycles needed to produce a material fit for its intended purpose.

Image:
L: Spiber

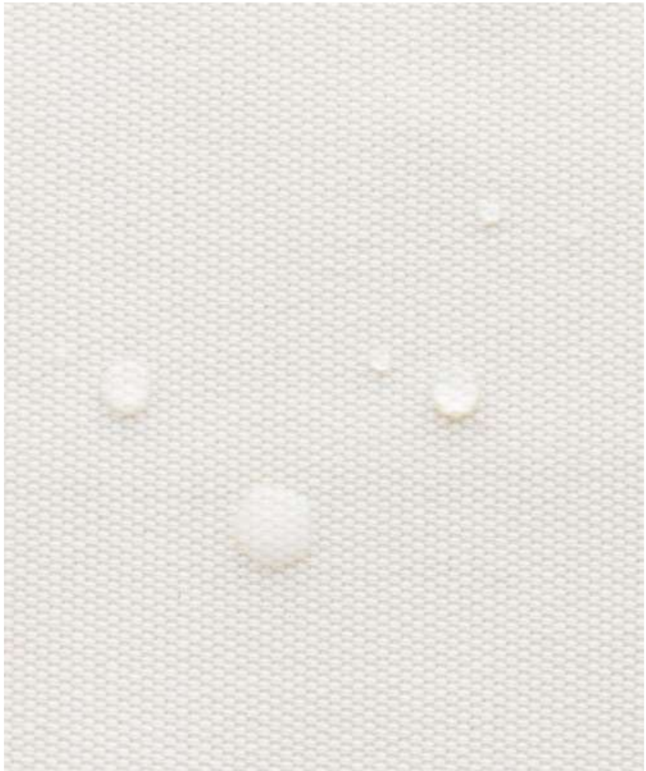
"IT TOOK ABOUT **ONE YEAR** ON WHAT WE'LL CALL FUNDAMENTAL SCIENCE, **ONE YEAR** DEDICATED TO REALLY DESIGNING AND DEVELOPING THE PRODUCTION CYCLE, WHICH IS ABSOLUTELY CRITICAL TO GETTING IT RIGHT, AND **TWO YEARS** OF WHAT I WOULD CALL 'APPLIED SCIENCE', ACTUALLY PUTTING IT INTO THE SUPPLY CHAIN AND GETTING IT TO WORK ON A FABRIC OR ON A MATERIAL THAT THE CONSUMER WOULD SEE."

GREG ALTMAN, CEO, EVOLVED BY NATURE

Before attempting to scale a technology, all of the above processes and stages of production need to be consistently replicable and have standardised operating procedures (SOPs) that can be translated to industrial manufacturing facilities. In the case of Evolved By Nature, for their "activated silk" textile coating, CEO, Greg Altman estimated that:

"It took about one year on what we'll call fundamental science, one year dedicated to really designing and developing the production cycle, which is absolutely critical to getting it right, and two years of what I would call 'applied science', actually putting it into the supply chain and getting it to work on a fabric or on a material that the consumer would see."

These companies are often built on the shoulders of many years of deep research and development and technical expertise. This was emphasized by most of the interviewees we spoke to, that what seems like a quick route to market is often not what it seems. Charles Dimmler, CEO of Checkerspot, emphasized this when discussing the important role that Solazyme, the company he worked at prior to Checkerspot, played in laying the groundwork for Checkerspot's success. Solazyme, now known as TerraVia, focused on harnessing the power of algae to produce specialty food ingredients for the food industry.



Developing new materials and processes takes time, learning and deep expertise as Charles summarises here:

"It's important to flag that what we're doing is built on the shoulders of past experience and that that experience (was) at Solazyme started in 2003. It really started to pick up momentum in 2008. So if you were to start the clock it took from 2008 to 2014/ 2015, about six plus years to get to commercial scale manufacturing. Checkerspot is building on a lot of the know how and lessons learned from that experience. And I feel like that's a really important qualifier because if I'd say Checkerspot was founded in the summer of 2016 - we're four years old and we have three products on the market, that would convey that Checkerspot has somehow done something extraordinarily unique in bringing a product to market at a ridiculously fast pace. And I feel that that's a misrepresentation."

Images:
T: Checkerspot / Adam Clark, @acpictures, Pep Fujas, freeskiing pioneer& VP of Marketing & Product at WNDR Alpine, using the brand's skis in the Wasatch Range, Utah.
B: QWSTION BANANATEX Fabric

Material Development Choices

FEEDSTOCK

When developing materials grown by microorganisms, as with any living thing, they need nutrition in order to thrive. In industrial biotechnology, what an organism is fed is referred to as a "feedstock" (a carbon source). Multiple factors have to be considered when selecting which type to use. The first is that there may be existing scientific literature detailing the efficacy of certain types of feedstock in relation to certain species of organisms, which helps speed up development timelines. Secondly, it may be that an organism needs a certain quality of nutrition that can only be obtained from a specific carbon source at this time. There may be economic and environmental implications associated with cleaning up a feedstock that comes from a waste stream. Additionally, there may be choices dictated by geographical availability of different biomass sources.

Image: **Bolt Threads**

Finally, all fermentation technologies are aiming to achieve the highest possible titer for any given organism. Many innovators have plans to move away from feedstocks sourced from plants that could potentially also be used as food (often referred to as 1st generation feedstock), but economically it may not be possible to meet the desired price point with any other type of feedstock for their first product. It is crucial to ask questions around each innovator's specific technology, why they are using the chosen feedstock, and what, if any, plans they may have to transition to a different one. For instance, there is growing interest in using greenhouse gases (GHGs) as potential feedstocks where a fermentation process actively sequesters carbon oxides or methane. The technologies engineering organisms capable of this are complex and time consuming, although a few companies, such as LanzaTech, are starting to offer products made in this way at commercial scale.

Overall questions around feedstock should be taken on a case by case basis. For example, what is the environmental impact of the feedstock an innovator is using in their particular geography and ecosystem? As with questions around end of use, it is impossible to make sweeping generalizations around feedstocks and impacts (see section 5 for further analysis).

"The commercial bioprocess technologies which have been developed to date by Genomatica utilize sugar as the feedstock. There are several factors which may influence the source of feedstock used in biochemical production. One must consider the balance of economics, quality of the feedstock and region for commercial production. Technologies typically require a particular quality of feedstock. If the sugar specification is inferior one could consider to either further process the sugar to improve its quality or optimize the biochemical technology to be able to utilize an inferior grade of feedstock. In North America, the predominant source of sugar is corn while in Europe there is a greater diversity of sugar source options - such as wheat, corn, and sugar beet. In Asia there is also a greater variability of sources of sugar, depending on the country"

Lisa Kennedy, Director Business Development, Genomatica

CHEMISTRY

In the same way that choices need to be made on feedstocks during research and development, decisions also need to be made on the types of chemistries which will be used in the creation of an end product. Many brands have RSL and MRSLs (restricted substances list and manufacturing restricted substances list) that they share with their innovator partners, these help provide guardrails on the types of chemistries that can be used in both materials and their manufacture. However, through the interviews innovators overwhelmingly also spoke to their own values as guiding principles in the selection and use of chemistries in their processes. And that these principles need to be established and practiced from the outset when developing new materials. In addition, navigating choices around chemistry can be further complicated by chemical suppliers:

"One of the most important tools for evaluating potential chemical inputs is looking at the toxicology of these ingredients, which can be tricky because ingredients tend to be proprietary and it's not necessarily obvious what is in a chemical product. It's also about finding cost effective tools to help navigate those challenges."

Jamie Bainbridge, VP of Product Development, Bolt Threads

"ONE OF THE MOST IMPORTANT TOOLS FOR EVALUATING POTENTIAL CHEMICAL INPUTS IS LOOKING AT THE TOXICOLOGY OF THESE INGREDIENTS, WHICH CAN BE TRICKY BECAUSE **INGREDIENTS TEND TO BE PROPRIETARY AND IT'S NOT NECESSARILY OBVIOUS WHAT IS IN A CHEMICAL PRODUCT.** IT'S ALSO ABOUT FINDING COST EFFECTIVE TOOLS TO HELP NAVIGATE THOSE CHALLENGES."

JAMIE BAINBRIDGE, VP OF PRODUCT DEVELOPMENT, BOLT THREADS

During development, an innovator may elect to experiment with a broader range of available chemistries to understand successful directions before later narrowing that search in line with their own internal or partner's guidelines for chemical usage:

"When performing research, no matter if on a biological or chemical level, it can be common to make use of frequently used and established compounds or techniques, to validate their effect on the transformations that one intends triggering. When working on such aspects with some of our specialized partners we have been informed that occasionally, at early stages, they consider testing traditional approaches or potentially hazardous compounds, with the scope of gaining preliminary insights and learn from those, for then moving on to the creation of innovative formulations and responsible transformative processes. In short, on a fundamental research level, one could say that some minor impact can still be found – however, as a company, we do not allow any potentially critical compound to be integrated in our products or as part of the manufacturing processes leading to their creation."

Maurizio Montalti, founder & Managing Partner, Mogu

Sometimes certain chemistries may be needed in order to meet performance standards dictated by an end application. Such as when a new material is expected to perform as well as its traditional counterpart which does use these chemistries:

"We essentially never use any chemicals in post processing the product, most issues we had with that was definitely around textiles, because of the durability question and that's one of those areas where you're almost really making a choice sometimes between durability and then end of life compatibility"

Eben Bayer, CEO, Ecovative

IMPACTS & END OF USE

In many ways the development of a new material is a series of choices and compromises, and as the above quote attests you cannot always have everything you want. One choice will affect another, for example, some materials may need some kind of crosslinking in order to stabilise them and prevent degradation, but this same act of fixing the material may affect its ability to degrade at the end of its life. However, what came through clearly during our interviews is that aspects like end of use, just as with chemistry, need to be taken into consideration from the beginning. **"You need to think about end of life from the very start".**

Maurizio Montalti, Founder & Managing Partner, Mogu

What also needs to be considered from the outset is impacts and hotspots (a further section of this report deals with this in more detail). Again, many of the innovators interviewed spoke to the value of assessing impacts and hotspots early on in development and that identification of these things actively informs development. As with all aspects of development there are often decisions to be made as to which to focus on, **"knowing which hotspot you're going to go after lets you do better because you won't be great at everything always."**

Eben Bayer, CEO, Ecovative

Done correctly, identifying and developing with potential impacts in the forefront of mind, benefits both the environment and bottom line; **"efforts to reduce the environmental impact are basically efforts to increase efficiency, reduce the inputs, which ends up reducing both the cost and environmental footprint"**

Kenji Higashi, Director, Spiber

Images:
L: Fermented Biomass, Courtesy of PURA, by Mogu
R: Mycelium Rucksack, Courtesy of PURA, by Mogu

“EFFORTS TO REDUCE THE ENVIRONMENTAL IMPACT **ARE BASICALLY EFFORTS TO INCREASE EFFICIENCY,** REDUCE THE INPUTS, WHICH ENDS UP REDUCING BOTH THE COST AND ENVIRONMENTAL FOOTPRINT”

KENJI HIGASHI, DIRECTOR, SPIBER

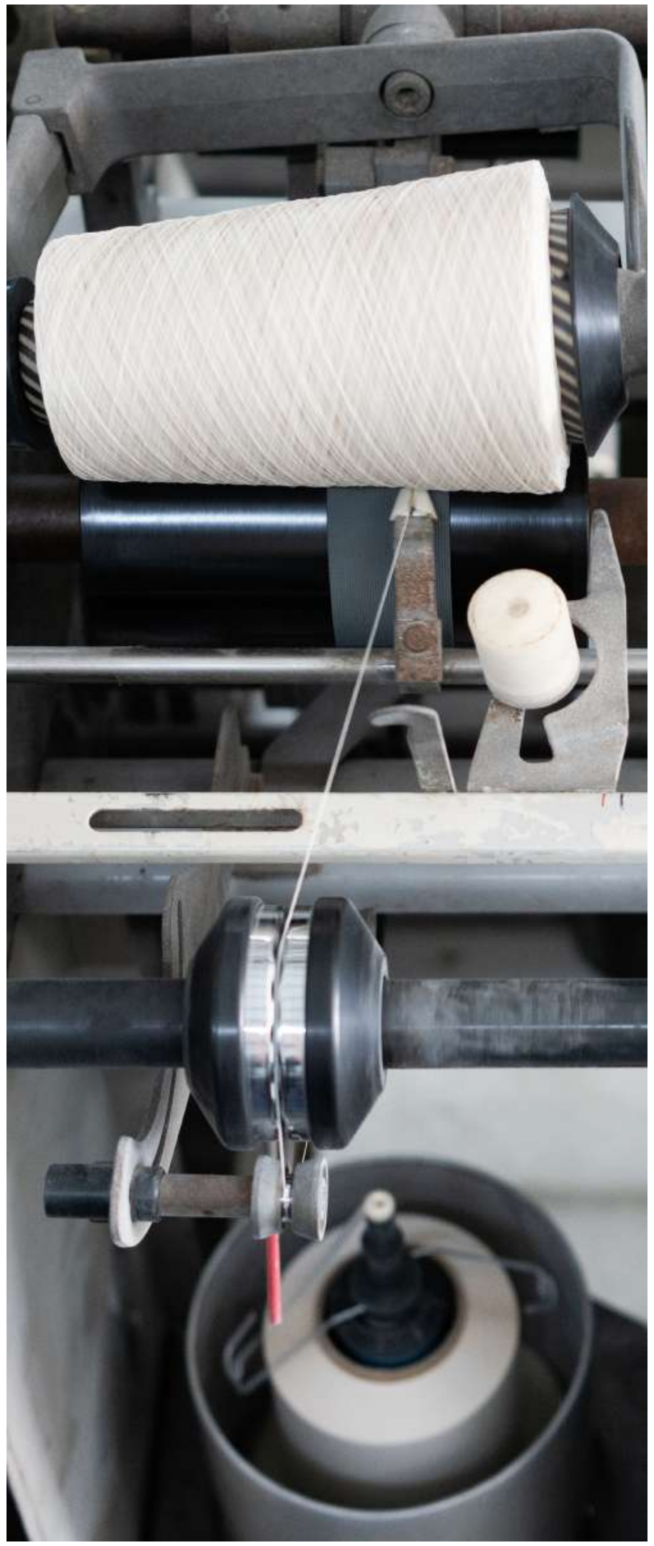
DEVELOPMENT PARTNERSHIPS

As innovators continue to develop their materials some may choose to partner strategically for support with technical development. As mentioned previously, the majority of startups in this space are the equivalent of several companies in one and can benefit from support from experienced technical partners. These decisions can help speed up development timelines and also negate the need to recruit and build in house expertise, which is both difficult and time consuming. An example of this is the partnership between Bolt Threads and German tannery HELLER-LEDER announced in 2019:

“Innovation means renewal and diversity. And diversity in the choice of sustainable materials is always positive. Therefore, we at HELLER-LEDER have decided to support the California based company BOLT THREADS in the research, development and production of the novel material MYLO.”

Thomas Strebost President, & Frank Fiedler CEO, HELLER-LEDER

Partnerships such as these can help both in the research and development stage of a material but are also critical to achieving an industry expected standard as a material innovation scales.



“KNOWING WHICH HOTSPOT YOU’RE GOING TO GO AFTER LETS YOU DO BETTER BECAUSE **YOU WON’T BE GREAT AT EVERYTHING ALWAYS.”**

EBEN BAYER, CEO, ECOVATIVE

Images:
L: QWSTION BANANATEX, Yarn-Spinning
R: MycoFlex™, Ecovative

SCALING

MEASURE YOUR TECHNOLOGY READINESS LEVEL - TRL How technology ready is your service/ product?		
0	**IDEA** Unproven concept, no testing has been performed	IDEA
1	**BASIC RESEARCH** You can now describe the need(s) but have no evidence	
2	**TECHNOLOGY FORMULATION** Concept & application have been formulated	
3	**NEEDS VALIDATION** You have initial 'offering'; stakeholders like your slideware	
4	**SMALL SCALE PROTOTYPE** Built in laboratory environment ('ugly' prototype)	PROTOTYPE
5	**LARGE SCALE PROTOTYPE** Tested in intended environment	
6	**PROTOTYPE SYSTEM** Tested in intended environment close to expected performance	VALIDATION
7	**DEMONSTRATION SYSTEM** Operating in operational environment at pre-comnmercial scale	
8	**FIRST OF A KIND COMMERCIAL SYSTEM** All technical processes and systems to support commercial activity in ready state	PRODUCTION
9	**FULL COMMERCIAL APPLICATION** Technology on 'general availability' for all consumers	

Table 1:

Technology Readiness Levels adapted graphically from CloudWATCH2 Project

TECHNOLOGY READINESS LEVELS

This section explores some key considerations and implications of scaling biofabricated materials. As innovations progress from prototypes to pilot/demo, and then commercial production, what is considered scale and to whom? When we asked innovators about scale up, many, as they are still relatively early stage, are thinking about scaling from bench or lab scale to pilot or demo but few are at the stage of scaling a pilot plant to full scale commercial. However when we spoke to textile, chemical or leather manufacturers, scale isn't "scale" for them until it is capable of producing materials on the order of hundreds of thousands or millions of square feet/metres annually. This is also true of larger brands looking to be first movers in this space:

"(Re scale) We sell way more than a million pairs of shoes a day, and so the volume that we do and the scale that we have is massive, and unless scale is there and sets the integration into our supply chain, it's not going anywhere."

adidas spokesperson.

It is useful to refer to a technology readiness level (TRL) tool to understand what milestones a particular material innovation has achieved towards market readiness. See table 1[49] for an example of TRLs. Once a laboratory process is developed to a point where it is ready to be tested in a final application it is usually translated either to a pilot or demo plant. This is a small scale industrial process, such as a section of production line built in house.

"Scaling up is an iterative process moving from lab scale, to pilot to full scale. It's a balancing act around when to invest in what equipment - it's not a straight line."

Jamie Bainbridge, VP of Product Development, Bolt Threads

Some startups or technologies may choose, or be required, to outsource this phase to external facilities who have the necessary infrastructure, e.g. yarn spinning, fabric weaving, coatings etc. This could take months to years of further iteration, with materials even returning to R&D, before moving to the next phase of scaling. In some instances the pilot or demo stage may be merged into one. Learnings gained at the pilot/demo scale (TRL 7 or pre commercial) should then enable either the design of full scale production systems and commercial products, or have allowed for kinks to be ironed out so that a material is ready to drop in to a brand's supply chain.

In table 1 TRL 8 is applied to technologies that have early initial systems in place "to support commercial activity", level 9 is classed as "full commercial" whereby production enables broad availability. For material startups producing a biofabricated ingredient, for example an engineered protein, scale for TRL 8 might be the ability to produce (purified protein) in the range

"WE SELL WAY MORE THAN A MILLION PAIRS OF SHOES A DAY, AND SO THE VOLUME THAT WE DO AND THE SCALE THAT WE HAVE IS MASSIVE, AND **UNLESS SCALE IS THERE AND SETS THE INTEGRATION INTO OUR SUPPLY CHAIN, IT'S NOT GOING ANYWHERE."**

ADIDAS SPOKESPERSON

of kilograms that can be spun into fibers or mixed with other ingredients/chemistries. For sheet materials such as mycelium leather[50], TRL 8 might be in the realm of tens of thousands of square feet per year. For TRL 9 however, biofabricated proteins would likely be in tons, and sheet materials in the hundreds of thousands if not millions of square feet per year. The gap between TRL 8 and 9 is significant and is measured in years.

For investors and brands, concern around an innovator's ability to reach "scale" is usually referring to the transition from TRL 7 to 8: from pilot or demo to first commercial plant. Although it may not be until they reach TRL 9 that they are expecting to see a return or profit from this technology.

TIME TO REACH "SCALE"

When polled, the innovators in our study shared radically different timelines for scaling from lab-scale prototypes to market ready (which is still not necessarily the same as full scale commercial - TRL 9). This reflects how timelines can be technology dependent and how individual innovator's think about scale depending on where they are at in their own journey.

A simpler biofabricated molecule, such as a precursor chemical for another material, will likely be much faster than a biofabricated material created from scratch. For the latter, in addition to innovating at the biology level, it will likely require materials science, chemistry, and potentially further textile or tanning processes. Most interviewees, however, expected it to take between 5 to 10 years with further discrepancies caused by considering different start points for the R&D phase. For example, in a few instances, the duration of research already undertaken was factored either in the form of academic study or learnings carried over from previous industry experience prior to the company's founding, as discussed in the R&D section above.

"Invention to ubiquity, as you know, that is about a 40 or 50 year journey"

Phil Ross, CTO & co founder, MycoWorks

It is therefore not possible to state a definitive number of years to go from bench to commercial scale. Further, the pace of each company's progress is dependent on their access to capital along with development and partnership choices and opportunities. European startups typically struggle more with access to capital than those in the US:

"There's slower innovation in the EU due to lack of capital - the US can run faster, though the EU has access to more textile infrastructure such as mills and tannery resources."

Greg Altman, CEO, Evolved By Nature

TO OWN OR PARTNER?

Among the considerations of teams aiming to scale technologies as fast as possible are decisions around what assets to buy/build internally, employing their own precious capital, vs seeking out technology/ manufacturing partners with existing expertise/ infrastructure. According to Susan Schofer, VP Commercial at Modern Meadow:

"scaling it could be faster, slower, depending on how much you're relying on existing infrastructure"

Susan Schofer, VP Commercial, Modern Meadow

Advantages of owning/operating systems internally include having complete control over a process with immediate feedback enabling fast iteration, troubleshooting, and protection of trade secrets. However, building dedicated production plants will likely involve real estate purchases, international operations, specialist engineering and additional risk; if for example a technology needs to pivot or capacity turns out to be different than forecasted. This can all take years, even at an expedited rate, and once in place it may necessitate a further year to recruit and train staff to operate and refine a system so that it can reach capacity without hitch. The build out of multiple commercial plants around the globe is typically a decade long project.

Within the emerging biofabricated materials field there are already various examples of outsourcing various manufacturing phases to contract manufacturing organisations (CMO's). Modern Meadow has partnered with global fermentation leader Evonik to scale up production of their collagen proteins[51], while Bolt Threads and Mycoworks have both formed strategic partnerships with European tanneries for their mycelium leather materials (Heller-Leder in Germany and Curtidos Badia[52] in Spain respectively).

"We were lucky that the protein upscaling has been successfully done several years ago. The upscaling of the fiber however took some time as we had to extensively involve engineers, CMO's and other stakeholders"

Jens Klein, CEO, AMSilk

In general, most investors would rather innovators harness existing manufacturing infrastructure to reduce capital expenditure and accelerate scale up.

Image: **Bolt Threads**

"WE WERE LUCKY THAT THE PROTEIN UPSCALING HAS BEEN SUCCESSFULLY DONE SEVERAL YEARS AGO. THE UPSCALING OF THE FIBER HOWEVER TOOK SOME TIME AS **WE HAD TO EXTENSIVELY INVOLVE ENGINEERS, CMO'S AND OTHER STAKEHOLDERS**"

JENS KLEIN, CEO, AMSILK

“**BEING HANDED OFF** TO BIGGER COMMERCIAL TEAMS CAN BE CHALLENGING”

JAMIE BAINBRIDGE, VP OF PRODUCT DEVELOPMENT, BOLT THREADS

SUPPLY CHAIN READINESS

For innovations that need to drop in to existing supply chains there can be specific challenges to scale. In order to understand a product’s performance, an ingredient or material already needs to be developed to the point where it is ready both technically, and in the quantity required, to even run on a commercial production line for the first time (which may require 100’s of feet of material or thousands of gallons of solution). Once those test results are in, the ingredient or material may still need to return to R&D for further iteration.

While some innovators may feel brands should make compromises in manufacturing, durability and/or aesthetics to accommodate the introduction of new materials into their products, the reality is that most brands will have similar, or in some cases higher, expectations for new material offerings. Unlike software or hardware, there is no minimum viable product for materials (MVP). Depending on the brand, expectations may be either quantitative; with established performance test targets and methods in place, and/or qualitative; where materials will be judged alongside existing supply chain offers.

One of the challenges for startups wanting to work with global brands like adidas is that the existing supply chain has: **“invested heavily in certain assets used to turn crude oil into materials...they’re very committed to using those assets for as long as possible which posed a significant barrier”.** adidas has found that some startups underestimate how the big chemical companies intend to use this same machinery for many years to come. Rather than imagine there is a different route to manufacture, the brand cautions that it’s about understanding **‘how do we fit (and add value) into that existing supply chain?’**.

“Something we really look for in terms of integration is that partner or startup understanding the supply chain and where they fit in. We’ve often struggled if partners just think that we’re going to reinvent the wheel and create a whole new supply chain. What works really well is when partners understand: this is our role, this is where we fit in, and they have some understanding of the partners in between us that it takes to commercialize something.”

adidas spokesperson.

Once partnership agreements are in place is when the work really starts. It may seem like the biggest hurdle is signing a deal with a renowned brand but it is unlikely the people who were involved in those discussions are the ones who will follow through the project as it progresses internally:

“Being handed off to bigger commercial teams can be challenging”

Jamie Bainbridge, VP of Product Development, Bolt Threads

Image:
QWSTION BANANATEX, Weaving Preparation

The original internal brand champion may move roles meaning new supporters need to be found or created, or it may simply be that initial contact is not the one who oversees material integration into the supply chain. Constantly engaging to build close, collaborative relationships is vital. It is also worth acknowledging differences in cultural expectations. Europeans tend to place more emphasis on getting to know partners on a personal level, whereas in the US it can be more transactional. Balancing those expectations for both sides should not be underestimated when a collaborative journey will likely last years and problems can only be solved together.

REGULATORY

Certain technologies have unique challenges. Any process involving the shipment of live engineered organisms, for example, will encounter regulatory hurdles ensuring partner facilities are GMO compliant before they can receive supplies. While there are established systems in place for safe handling, such as The Cartagena Protocol, it raises interesting questions for textile supply chains who may be dealing with such certification issues for the first time.

“SOMETHING WE REALLY LOOK FOR IN TERMS OF INTEGRATION IS THAT PARTNER OR STARTUP **UNDERSTANDING THE SUPPLY CHAIN** AND WHERE THEY FIT IN”

ADIDAS SPOKESPERSON

THE ISSUE IS NOT LACK OF BRAND ENGAGEMENT, IT IS SIMPLY THE EXTENDED TIME IT TAKES TO CLOSE THE GAP BETWEEN EARLY PROTOTYPES AND REFINING MATERIALS TO MATCH THE LEVEL OF PERFORMANCE, FINISH AND MANUFACTURABILITY EXPECTED BY THOSE BRANDS.

AVAILABILITY OVER HYPE

There is no shortage of brands looking for sustainable material innovation. Recent global events have only served to intensify that interest. While it is true that little is on offer to the consumer at this time, it is certainly not due to a lack of interest on the part of brands. It is easy to jump to the conclusion that if these biomaterial innovations are not yet available to consumers, the remaining challenge must simply be to find brands willing to work with them. That is a myth.

Most of the more mature material innovators have a pipeline of brands from every possible sector wanting to sample these new materials. Some companies in the biofabrication space have exclusive partnerships with luxury and sport brands that extend back years already. The issue is not lack of brand engagement, it is simply the extended time it takes to close the gap between early prototypes and refining materials to match the level of performance, finish and manufacturability expected by those brands. Only once those targets are met, and a process is locked down, can a manufacturing system be scaled to meet both initial limited edition launches, and then be followed by volume supply in the not so distant future. The gap between limited edition quantities and readily available commercial volumes is still likely to be a couple of years or more.

A challenge for entrepreneurs is that they are under pressure from investors to validate demand or evidence market traction early on. This often results in conversations with brands (and media) that happen long before technologies are fully understood or realistic timeframes for scaling are in place. It requires discipline and focus to not be swayed by many different brands all asking for different properties from a material technology still in development. Unsurprisingly, impatience or disillusionment can set in when launches take many years rather than months to come to fruition. It's a fine line to walk for innovators, but what all are agreed upon is that developing new materials is nothing like building an app. The myriad complexities presented by novel material development need to come with realistic time to market expectations.

"That first million square feet per year is 100% allocated to our current top brand customers"[53]

Dan Widmaier, CEO & co-founder, Bolt Threads

Image: Mylo™ by Bolt Threads

"THAT **FIRST MILLION SQUARE FEET PER YEAR IS 100% ALLOCATED** TO OUR CURRENT TOP BRAND CUSTOMERS"

DAN WIDMAIER, CEO & CO-FOUNDER, BOLT THREADS

PARTNERING

WHEN TO ENGAGE & TIMELINES

For many startups in this space, when and how to engage with brands is a complicated issue to navigate. There is often pressure to obtain things like LOIs (letters of intent) from brands very early on, which are desirable especially for investors concerned about proving market traction. These early conversations can set up unrealistic expectations on both sides of the table. They can cause partnerships to be put in place too early or cause them to fail if the technology moves in a different direction. Additional pressure can come from the fashion and textile industry itself as brands actively search for sustainable material alternatives. The appetite for innovation and new materials is so strong that, combined with extensive media coverage and a lack of technical understanding, brands are reaching out to very early stage material startups who simply are not ready for the kinds of questions they will encounter. Media stories often fuel unrealistic expectations by portraying single researchers as a "company" with a market ready solution - these may in fact be nothing more than an experimental material design project. Though this interest can trigger a decision to form a company, in either case, what it means is that there is brand engagement and pressure from very early on - long before any materials are ready to be sampled.

For many it's a balancing act of both socialising their technology, trying to be realistic about development timelines, and clearly articulating how and where a brand can be additive.

"This journey is a tough one because there's so much interest in these new materials. There's lots of opportunity, but with materials, the opportunity really can't be activated until there's something concrete to work on. So I'm not sure that there's much to be done in those earlier days. I do think engaging is good. There's learning on both sides, but at the same time I'm not sure how useful it is. I think with any new field it's probably stops and starts in terms of socializing the technology, getting people excited about it, realizing that, oh, it's too early. I think it's always going to be hard for brands who are used to dealing with finished materials and trying to understand what is meaningful for them to get engaged in an earlier stage in a way that's productive for both sides."

Susan Schofer, VP Commercial, Modern Meadow

In some cases innovators may try to keep brand conversations at bay for as long as possible, and for others they have developed new models of engagement to help focus conversations and begin them earlier in the process. For example, one startup interviewed has created a form to capture answers to key questions from brands - from helping to understand goals, to amounts of materials needed for sampling:

"Identifying the right time to engage with brands is something that we've struggled with defining. And at one point, we thought, well, we're not ready yet. We're not ready to talk to anyone. And then we flipped our perspective, and decided it's better to start a conversation sooner rather than later, to build trust and confidence in the relationship, open up the conversation a little bit and share as much information as possible. Establishing goals with the brands as soon as possible, defining what their intent is, understand the scope of work they want to achieve and within what timelines."

Aleks Gosiewski, Chief Operations Officer & cofounder, Algiknit

This establishing of goals and timelines, also enables startups to understand if there's a fit. For example, if it is a straight "send us some samples" request this may signal a warning bell and identify a brand that is not yet ready to engage as they likely won't have the patience to wait multiple years or deal with the uncertainty of how the final product may evolve over time.

"If we say, this material is going to take ten years - we don't want the response from brands to be; 'okay, well then talk to us in nine years when we're actually able to launch this'. Because the problem is we literally can't build our startup, at the beginning stages, unless we have this kind of brand interest and excitement."

Michelle Zhu, CEO & cofounder, HUUE

For other brands their size, minimum volumes, and business model mean they are not likely to be early adopters. It can also be especially challenging if they do not own any of their manufacturing.

Another factor in deciding when to engage is that these types of new partnerships can be years in the making, making it a further difficult balancing act.**"It could be seven years before getting them to sign on the dotted line, from initial conversation or approach to actually making a deal - even that's fast"** (Phil Ross, CTO & cofounder, MycoWorks). Conversations that can be relatively fast paced in the beginning slow down when they reach contractual and legal discussions. The impact of those discussions on timelines and planning, forces innovators to make decisions as to whether they continue production in good faith or delay until contracts are signed. This becomes a calculation of risk.

"THIS JOURNEY IS A TOUGH ONE BECAUSE THERE'S SO MUCH INTEREST IN THESE NEW MATERIALS. THERE'S LOTS OF OPPORTUNITY, BUT WITH MATERIALS, **THE OPPORTUNITY REALLY CAN'T BE ACTIVATED UNTIL THERE'S SOMETHING CONCRETE TO WORK ON."**

SUSAN SCHOFER, VP COMMERCIAL, MODERN MEADOW

“IF WE SAY, THIS MATERIAL IS GOING TO TAKE TEN YEARS - WE DON’T WANT THE RESPONSE FROM BRANDS TO BE; ‘OKAY, WELL THEN TALK TO US IN NINE YEARS WHEN WE’RE ACTUALLY ABLE TO LAUNCH THIS’. BECAUSE THE PROBLEM IS **WE LITERALLY CAN’T BUILD OUR STARTUP, AT THE BEGINNING STAGES, UNLESS WE HAVE THIS KIND OF BRAND INTEREST AND EXCITEMENT.”**

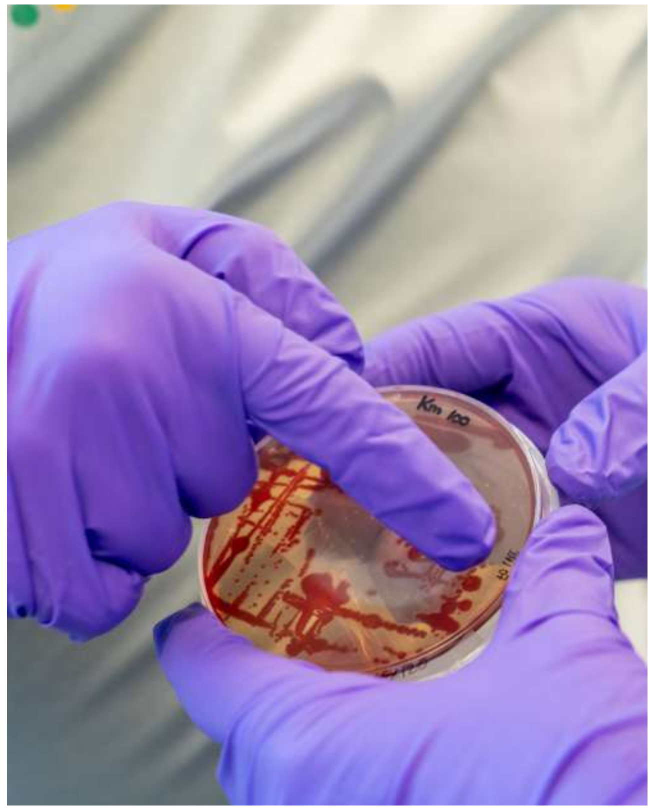
MICHELLE ZHU, CEO, HUUE

With the above said, for biofabricated material partnerships, a key issue that can cause tension is timelines:

“Because innovation in the biomaterials space is so new, it can be very difficult to predict timelines. Not only are these startups creating new materials and processes, but trying to do so in a more sustainable way. As a result, innovators can find themselves in a situation where the R&D roadmap is overly optimistic and needs to be revisited. This is unavoidable in many respects, but something to keep in mind during the process – it’s a good practice to add buffer into the calendar.”

Christine Goulay, Head of Sustainable Innovation, Kering

This volunteering of optimistic timelines often comes from startups who are trying to predict complex technology development years out into the future. It is no easy task. Throughout the interview process both innovators and brands spoke to a need for more transparency and understanding on this issue. A key learning is that neither party has a blueprint for this new breed of materials. We can make forecasts for how long elements of a technology may take to develop based on other sectors, but bringing all parts together still allows much room for unpredictability. This field is also seeing many brands entering into new types of partnerships and being involved with material development at much earlier stages than they have ever experienced before. This can sometimes lead to project fatigue when a technology takes years not months to come to fruition.



Images:
L: Stella McCartney x Colorifix (image credit Presstigieux)
R: Colorifix

WHAT MAKES FOR SUCCESSFUL PARTNERSHIPS IN THIS SPACE?

TYPES OF PARTNERSHIPS / ENGAGEMENT

Many of the innovators in this space are doing work that would historically have been conducted in house at large corporations who are able to financially support long term R&D. In order to finance their companies they have turned to a mix of grant, venture capital and debt funding. Many startups also have interest in strategic financial investments from brands in exchange for things like first mover advantage, exclusivity and so on. Issues of exclusivity can be challenging to balance as expressed by Kenji Higashi at Spiber; **“Usually the brand wants some degree of exclusivity and that is sometimes a good thing for us as well, especially if it's a limited period of time. But when they want too much exclusivity, that can limit our growth and can be a problem.”**

ABOVE AND BEYOND A MATERIAL'S TECHNICAL PERFORMANCE, **HOW DO YOU BREAK DOWN LOOK AND FEEL INTO QUANTIFIABLE AND TESTABLE METRICS?**

Committing significant funds to a partnership enables a brand to have some input into material development, rather than simply waiting in line to buy the first generation material a startup produces. This kind of investment, however, is uncommon for most of the fashion industry. Expectations tied to investments are where issues of timelines and scaling can quickly become pressing:

"One of the primary ways to help support innovators in their journey to scale is by providing market feedback and expertise during the R&D phase. We share information on our Kering sustainability standards, technical requirements, and try to help provide access to testing in our supply chains. This accompaniment is an investment on our side, but one that is instrumental in arriving at a market-ready innovation and achieving our Group's sustainability objectives."

Christine Goulay, Head of Sustainable Innovation, Kering

As already mentioned, there are still many unknowns in this domain, especially around the gap between R&D and reaching commercial scale.

"It's not just the timeframe, it's also a commitment. So you tell someone, they'll get something in five years if you commit now. And that is a very hard discussion to have in our industry, as it is not made for offtake agreements. And that is what many of these companies actually need. And I see that as a gap: how do we commercialize these technologies?"

adidas spokesperson

Many are still exploring what exactly are the best financing models and types of engagement between innovators and fashion brands to be most productive for both parties. The most successful partnerships are those built on true collaboration, where brands open up their supply chain for innovators helping them to connect:

"The biggest level of support and commitment is know how, giving us access to information and supply chain so that we can better understand where we fit, especially early on"

Orr Yarkoni, CEO & Founder, Colorifix

FINANCING

Boston Consulting Group and Fashion for Good's co-authored report, 'Financing the Transformation in the Fashion Industry: Unlocking Investment to Scale Innovation' explores some of the challenges around bringing hard technology solutions (ie.those that require developing physical, capital intensive assets) to market at scale.[54] The report identified that there are two points in the development process that are most challenging to finance. Firstly innovators find it difficult to secure financing to develop a minimum viable product, and, secondly, they struggle in the scaling phase when trying to reach commercial volumes. Some of the reasons for this shortfall are a limited awareness of the opportunities but also lack of technical expertise. Innovation in the fashion industry is a relatively recent development so investors have had limited exposure to the size of the opportunity. Alongside this there are often misaligned incentives between brands and manufacturers, the former capturing most of the value from sustainability whilst the latter are largely responsible for the costs. New innovation often has to compete with commoditized prices of existing solutions, a challenge in itself. To overcome the barriers all parties must work collaboratively to drive change, the roles of these different stakeholders are outlined in Figure 5.

However, MycoWorks recent raise of $45m in Series B financing to help fund their new Reishi™ production plant in Emeryville, California, is evidence of the company successfully moving into their next phase of scaling[55].

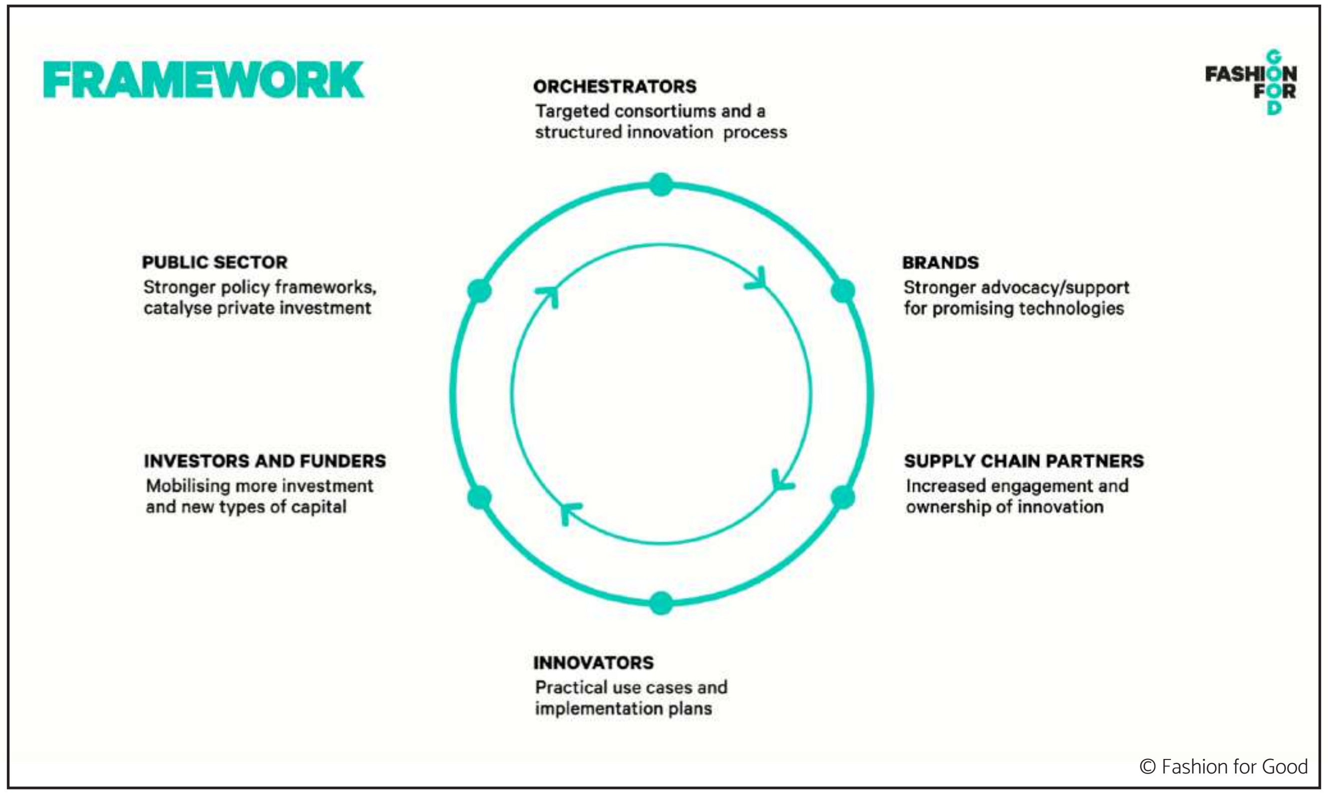


Figure 5: Fashion for Good & Boston Consulting Group

CONSORTIA

As mentioned above, exclusivity models, whilst helpful in some instances, have the potential to be limiting to the field's long term growth. To help mitigate this and move faster in scaling innovations, many industry players such as brands and manufacturers are looking to consortia. These types of engagement models were often discussed during our interviews, with a few startups actively seeking to put these in place. Some in the field have already announced powerful partnerships. For example the consortium formed by startup Bolt Threads with adidas, Kering, Lululemon and Stella McCartney, to launch it's Mylo 'unleather' in 2021[56]. As recommended in the report; "Forming consortia of a few brands, supply chain partners, investors, and technical experts that believe in the value of a particular technology allows the participants to concentrate their efforts and share risk, thereby accelerating innovation and commercialization. Orchestration and consortia are essential to helping innovators find the right support and financing, giving brands faster access to scalable technologies, and offering investors better opportunities."[57]

These consortium partnerships don't always have to be driven by the innovator. Fashion for Good has been instrumental in orchestrating these partnerships across different focus areas of the supply chain. They launched a first of its kind chemical recycling project in September 2020, bringing together a range of different stakeholders across the ecosystem to focus on scaling cellulosic chemical recycling solutions. Alternatively, opportunities also arise through grant funding like the Horizon 2020 program in Europe, which has enabled the launch of multi stakeholder initiatives looking to work together to tackle a particular challenge.

Image: **Modern Meadow**

MATERIAL DEVELOPMENT TARGETS AND FEEDBACK

Another key area of misalignment and tension can come in the form of material targets and feedback. Startups may have differing expectations as to the level of developmental help a brand can contribute. This can lead to a lack of clear material targets and quantitative data. Most fashion brands are unlikely to have in-house materials science or technical expertise. They won't directly be able to share quantitative data on required material performance. For many, their suppliers or factories may have that data, the brand has no need to build such capacity in house. Although we do see that this is changing, as some brands start to invest in and build up in house technical expertise with specialist innovation and sustainability teams.

The type of feedback they are keen to provide is guidance on aesthetics, handle or manufacturing expectations (eg will it last in a shoe?), but this will be qualitative in nature and unlikely to be backed by numerical data or test methodology. This qualitative feedback can often be a source of misalignment. The majority of startups teams in this space are scientifically trained, used to dealing with quantitative targets. Even when machine driven tests exist to determine a number, for example "softness", a material that achieves a desired target can still be deemed not "soft" enough or lacking the right "feel" by a design team. In science, where each experiment is designed to test one variable at a time, it can be incredibly difficult to design experiments when provided with samples as reference. Above and beyond a material's technical performance, how do you break down look and feel into quantifiable and testable metrics? It is a difficult process to develop experiments that try to alter one aspect of a material, for example drape, and ask a brand to give feedback on that and not the totality of a sample i.e. how it looks, feels etc etc.

Larger brands, and luxury groups such as Kering, are usually keen to share information on their sustainability standards, technical requirements, and try to help provide access to testing in their supply chains. Their goal is to ensure a market ready innovation that will meet their sustainability objectives.

A number of the innovators interviewed specifically spoke to seeking out brand partners with technical R&D capabilities in house. Phil Ross, CTO of Mycoworks expressed **"Brands also have to have their own internal R&D development system; otherwise, there are risks in both directions."**

These types of competencies are most commonly found in larger "technical" brands, such as outdoor or performance sport where internal departments have expertise that can work collaboratively with an innovator's technical or scientific team.

"So having a very, very strong technical R&D function is very important. I think a lot of companies have R&D functions to develop their own products. But usually, brands don't have R&D functions to develop the materials. So usually they'll buy materials that are ready to go. And their R&D starts from there, usually. So, having the capability to work at a layer deeper in the material development activities is, I think, something that is very important and something we look for in brand partners."

Kenji Higashi, Director, Spiber

"THE IDEA OF FINDING NEW WAYS OF MAKING MATERIALS THAT TYPICALLY COME FROM ANIMALS IS REALLY EXCITING. SO WE'VE HAD VERY LITTLE BARRIER FOR INTEREST, AND WILLINGNESS TO TEST AND TRIAL THINGS. I THINK THAT **THE BIGGEST CHALLENGE THAT WE HAVE NOW** INTERNALLY IS EVERYONE'S KIND OF TIRED OF DOING PILOTS. WE DID ENOUGH OF THAT AND WE JUST REALLY WANT TO BE ABLE TO START OFFERING PRODUCTS."

STELLA MCCARTNEY SPOKESPERSON

SAMPLES & PROGRESS

As the saying goes, "seeing is believing", and samples of new materials are a way for startups to gain traction, for brands to see potential, and for both to track progress. However, when to first provide samples is an important decision for innovators, especially in the face of an industry used to asking for samples as routine. Algiknit has developed a form to share with prospective partners but they have yet to send out samples:

"When we engage with brands, one of the first things we have them do is complete a project form. It's become a standard procedure that we follow with everyone that we engage with. At the same time, we let brands know that we don't have that many samples available."

Aleks Gosiewski, Chief Operations Officer & cofounder, Algiknit

One of the reasons innovators may hold back, or be reluctant, in sending materials is that with a bench scale process it is often a time consuming endeavor to produce them. According to Gosiewski, **"At the small scale that we produce in our labs, the reality is that it can take 2 people a full day to make a sample"**.This can lead to a balancing act, for sometimes very small teams, between prepping samples and continuing R&D, demanding constant decisions on where to focus resources.

There may also be a need to do fundamental R&D work which can lead to important progress but that won't necessarily result in samples that look or feel different.

"We don't have enough team members for us to have both manufacturing and R&D going on in parallel. And so after we share samples, brands have to wait for us to go back into the lab and just do some of the fundamental strain engineering work and hunker down a little bit before we move into the next phase of the process. I know brands are driven by product and they want to see things, so I worry they'll feel like you're not productive unless you're running productions and putting stuff into their hands even though we are pushing as hard as we can."

Michelle Zhu, CEO & co-founder, Huue

In the last few years there have been several one off prototypes. Creating enough material for these can be relatively easy and because they are often not made in manufacturing facilities there is more tolerance for performance in production. However, as detailed above, there is a large gulf between being able to make a proof of concept and translating this into real scale. Increasingly there is less appetite for what are essentially press pieces. These early prototypes can also lead to fatigue within a brand. And it can also be a cause of frustration with consumers, for whom a two year wait might as well be forever.

"The idea of finding new ways of making materials that typically come from animals is really exciting. So we've had very little barrier for interest, and willingness to test and trial things. I think that the biggest challenge that we have now internally is everyone's kind of tired of doing pilots. We did enough of that and we just really want to be able to start offering products."

Stella McCartney spokesperson

So once a brand has launched a limited edition product run, most are looking to quickly ramp volumes and expect downward price adjustment accordingly.

PRICE

One of the main areas of focus for new innovations, biofabricated materials being no different, is their price. At first launch new technologies are often severely limited in quantity and command a high price. The price is reflective of both the years of investment in R&D and infrastructure, and building an organization from scratch, combined with a process that has yet to be optimized for scale. But just as with other technologies, economies of scale will eventually bring down prices over time. The reason many of the early innovators in this space targeted materials such as silk and leather was the potential to achieve a premium price.

Price is one aspect around which multiple brands interviewed said they had some maneuverability, this inevitably varies between luxury and mass market players and at different scales. However, for startups going after more mass applications, it's important to recognize that even if there is tolerance early on, that even this only runs into single digit differences in the current prices brands are paying for materials:

"We're willing to take a premium at the beginning, we have a good idea of what the brand can take in the long termand that's a single digit percentage rather than 10 X or anything like that. So all of these things we compromise on in the short term, but there has to be a route to a mid and long term where those things are addressed."

adidas spokesperson.

Image: Spiber, Brewed Protein™ and cotton blend T-shirt by sacai

"WE'RE WILLING TO TAKE A PREMIUM AT THE BEGINNING, WE HAVE A GOOD IDEA OF WHAT THE BRAND CAN TAKE IN THE LONG TERM AND THAT'S A SINGLE DIGIT % RATHER THAN 10 X OR ANYTHING LIKE THAT. SO ALL OF THESE THINGS WE COMPROMISE ON IN THE SHORT TERM, BUT THERE HAS TO BE A ROUTE TO A MID AND LONG TERM WHERE THOSE THINGS ARE ADDRESSED."

ADIDAS SPOKESPERSON

IMPACT ASSESSMENTS

THE SCOPE OF THE ASSESSMENT IS PREDETERMINED AT THE START AND THEY ARE FREQUENTLY USED TO **IDENTIFY HOTSPOTS AND MEASURE TOTAL IMPACT**.

Image:
R: Brewed Protein™ polymer, Spiber

IMPACT ASSESSMENTS

"IT'S GOOD TO UNDERSTAND THAT WHEN A COMPANY IS ASKING FOR AN LCA, IT'S NOT NECESSARILY REALLY ASKING FOR AN LCA, IT'S QUITE OFTEN ASKING FOR AN INDICATION THAT THERE'S SOME SUSTAINABILITY BENEFIT..."

ADIDAS SPOKESPERSON

Image: AMSilk

It is estimated that the fashion industry accounts for around 4% of global GHG emissions, with 38% of these emissions coming from raw material production, preparation and processing and 3% from end of use[58]. This clearly demonstrates that there is a significant opportunity for brands to reduce their overarching footprint by transitioning to lower impact materials.

A brand's impact can be split into five tiers:
Tier 0 - stores, warehouse, offices
Tier 1 - Assembly
Tier 2 - Manufacturing
Tier 3 - Raw Material Processing
Tier 4 - Raw Material Production

Kering's 2019 publicly available Environmental Profit & Loss (EP&L) data reveals that the Tier 4 raw material production makes up 65% of the group's overall footprint A significant portion of this total relates to the use of leather and animal fibers, where the greatest impacts are in terms of land use and greenhouse gas emissions, mostly caused by raising livestock and material waste throughout the supply chain. Biofabricated leather/animal fibers thus have an important potential for impact reduction, eliminating the need to source from livestock and enabling more efficient production processes. In that regard, the partnership with Bolt Thread's Mylo represents an especially exciting opportunity. Of course, as with all new materials, when production moves beyond pilot scale, the impacts need to be made public. Water, energy and chemistry impacts are often high with leather so measuring and comparing these impacts with leather alternatives is necessary for informed decision making.[59]

Although a challenge with new materials, it is crucial to be able to evaluate the environmental and social impact of these innovations, particularly when looking to replace existing materials or processes with supposedly improved alternatives.

The term impact assessment is broad and can cover different methods and ways of assessing a product or material's impact. Life Cycle Assessment or LCA is the EU recommended method

LCA IS **A GENERAL METHODOLOGY** AND THE COMPLEXITY AND DEPTH OF THE OUTPUT IS VARIABLE DEPENDING ON BOTH THE REQUIREMENTS OF THE END USER AS WELL AS **THE STAGE AND MATURITY OF THE INNOVATION OR PROCESS.**

on how to conduct an impact assessment. An LCA can be thought of as an accounting methodology that outlines a clear approach and method for conducting such an analysis. It is commonly used to measure a product's environmental footprint from raw materials to end of use, often encompassing cradle to gate. The scope of the assessment is predetermined at the start and they are frequently used to identify hotspots and measure total impact.

Brands often ask to see an LCA but in most cases they do not actually need to see a full Life Cycle Assessment. Instead, they want to be able to track an innovator's key metrics, as well as the associated data and calculations to back up any claims.

"It's good to understand that when a company is asking for an LCA, it's not necessarily really asking for an LCA, it's quite often asking for an indication that there's some sustainability benefit. So my advice to companies is, understand early on what the key metrics are you're trying to change and get data on that."

adidas spokesperson.

Image: **Pili Inc.**

LCA is a general methodology and the complexity and depth of the output is variable depending on both the requirements of the end user as well as the stage and maturity of the innovation or process. For earlier stage innovators who might not have yet "locked down" their process it is not always possible to map all parameters through a full LCA. In this instance, startups can begin their impact assessment by doing a preliminary evaluation using available knowledge and insights and develop the assessment as they progress. The scope and breadth can be loosely attributed to the different stages of TRL readiness.

TABLE 2: "LCA AND SUSTAINABILITY" A GUIDE FOR STARTUPS AND BRANDS IN INNOVATION PROCESS

Using the TRL framework outlined in Section 4 of the report it can be grouped as follows:

	WHAT STARTUPS MAY CONSIDER DOING AT THIS STAGE	WHAT BRANDS ARE LOOKING FOR AT THIS STAGE
TRL 0 - 3 Idea	**Show the ambition**	**See the potential**
	● Startups make a simple LCA assessment estimating the potential of their innovation at scale. ● **Data:** use rough projections and try to benchmark with published values. ● **Impacts included:** maybe just one indicator to show benefit - e.g. only carbon footprint. ● **Format:** one page summary and a few pages documentation (aka 'third party LCA report*') Use LCA framework (ISO 14044) but make the estimation simple and short.	● Here brands need an indication that a technology has a sustainability potential and get a sense of how big it is. ● This will be used by brands in internal pitches to secure buy in and budget. Your documentation gives brand assurance you have done the calculations in the right way. ● Already here you may be asked about other impacts - but if you show the timeline when you plan to cover them the answer is usually accepted.
TRL 4-5 Prototype	**Show the roadmap**	**Ensure this is feasible**
	● Repeat your assessment with actual data from your prototype scale. Understand your footprint and what drives it ("hotspots"). What will it take to achieve your sustainability benefit as you scale? Adjust ambition as necessary. ● **Data:** primary data from your prototype scale. When benchmarking to other materials and processes ensure comparison is "fair". ● **Impacts included:** understand if there are potential trade offs of different impacts (e.g. carbon footprint better, toxicity worse); ● **Format:** min. one page summary and a few pages documentation (aka "third party LCA report*"). Use the LCA framework (ISO 14044) but only as detailed as needed.	● Here brands need to be ensured that you have understood the environmental impacts of your innovation enough that you can achieve the sustainability benefit at some point. ● You don't have to be there now, you just need to demonstrate how you plan to get there. ● This information will be used by brands to position the innovation internally and map how and when will this innovation contribute to achieving the brand's sustainability targets.
TRL 6- 7 Validation	**Demonstrate progress to brands**	**Demonstrate progress internally**
	● Repeat assessment using data from current state of production developments, mark the progress made on your roadmap as well as the potential challenges. ● **Data:** primary data from your current state ● **Impacts included:** as before, keep an eye on potential tradeoffs (e.g. carbon footprint better, toxicity worse. ● **Format:** min. one page summary and a few pages documentation (aka "third party LCA report*"). Use the LCA framework (ISO 14044) but only as detailed as needed.	● Here the brands need to see that you are working on it and making progress. This means that your commitment to the sustainability target is solid and the brand can be reassured you will get there. ● Brand also need to be sure there are no unpleasant surprises (e.g. tradeoffs in impacts) that may damage the brand's targets progress. ● This will be used to keep the innovation on good standing internally and ensure continuous support.
TRL 8-9 Production	**Enable Marketing**	**Ensure marketing is possible**
	● Here you need to have your results that show the achieved sustainability benefit of your current technology. Having an expert party making or checking your evaluation is useful. ● **Data:** primary data from your production scale. ● **Impacts included:** here the holistic set of indicators should be covered. ● **Format:** the minimum requirement here is still the same - the "third party LCA report*" - just keep in mind, this one needs to be shareable with the public if requested. So use the formal report format, and involve an external expert/consultant to make/review the report.	● Here the brands need to have a justification for making an external claim about sustainability of their products (e.g. marking product as "sustainable" on their ecommerce platform). Brands have to legally justify any product claims, so they will need a report that can be shared if requested. ● The LCA report will be used by brands to make and justify marketing claims for products. ● Important to understand that even with an LCA report performed by reputable consultants, brands can't make comparative external claims (e.g."twice better than cotton"). These claims require an externally reviewed report**

*The term "third party report" simply refers to a report prepared to be shared with any third parties (like brands), therefore does not require an external consultant. The third party report documents the minimum information about how you did the evaluation so the third party can interpret your results correctly. ISO 14044 clauses 5 and 6 describe which content this documentation needs to cover. While the name sounds scary the third party report can just be a couple of slides or a few page word document. Please note that the third party report is a requirement for any LCA results (even for one graph) shared outside of your organization;

** Externally reviewed LCA report: if you want to enable comparative external claims around sustainability for your innovation, either for the brands or for yourself (e.g. "most sustainable natural fiber") you need to do an external review process for the LCA report. This is a lengthy and expensive process, guided by the respective ISO standard ISO/TS 14071 and we only recommend to consider it if you have a good case for why it is needed. Not all brands will want to make comparative claims, and not for all products.

TRACKING DATA AND IMPACT HOTSPOTS

Whilst it's good to be clear on the benefits of a particular technology, it's equally important to identify and track unintended consequences that might arise from developing and scaling up the use of particular feedstocks or processes. In other words companies should have **"a consideration of the overall ecosystem of impact an innovator is engaged in"**[60] and be open about their process.

More mature innovators advocated that measuring their impact as their technology and company developed, enabled them to make decisions prospectively not retrospectively and avoid unforeseen challenges later down the line. A number of the companies interviewed had set their own "sustainability" guiding principles early on, so they had clear internal parameters and guardrails that they were working within. This enabled more focused R&D and material development as well as allowing them to clearly articulate their primary sustainability benefit. Real time tracking meant they could identify and address byproducts that might have arisen through particular processes. For example, picking up contaminants during the fermentation process from the equipment being used. Early chemical compliance tests and biocompatibility screening also helped mitigate this.

Some companies were not comfortable sharing data when they were still developing their technology, however, they all valued partners asking these questions. It was evident that long term partnerships founded on openness helped facilitate collaborative development decisions. It also allowed innovators to understand the intentions behind brand requests.

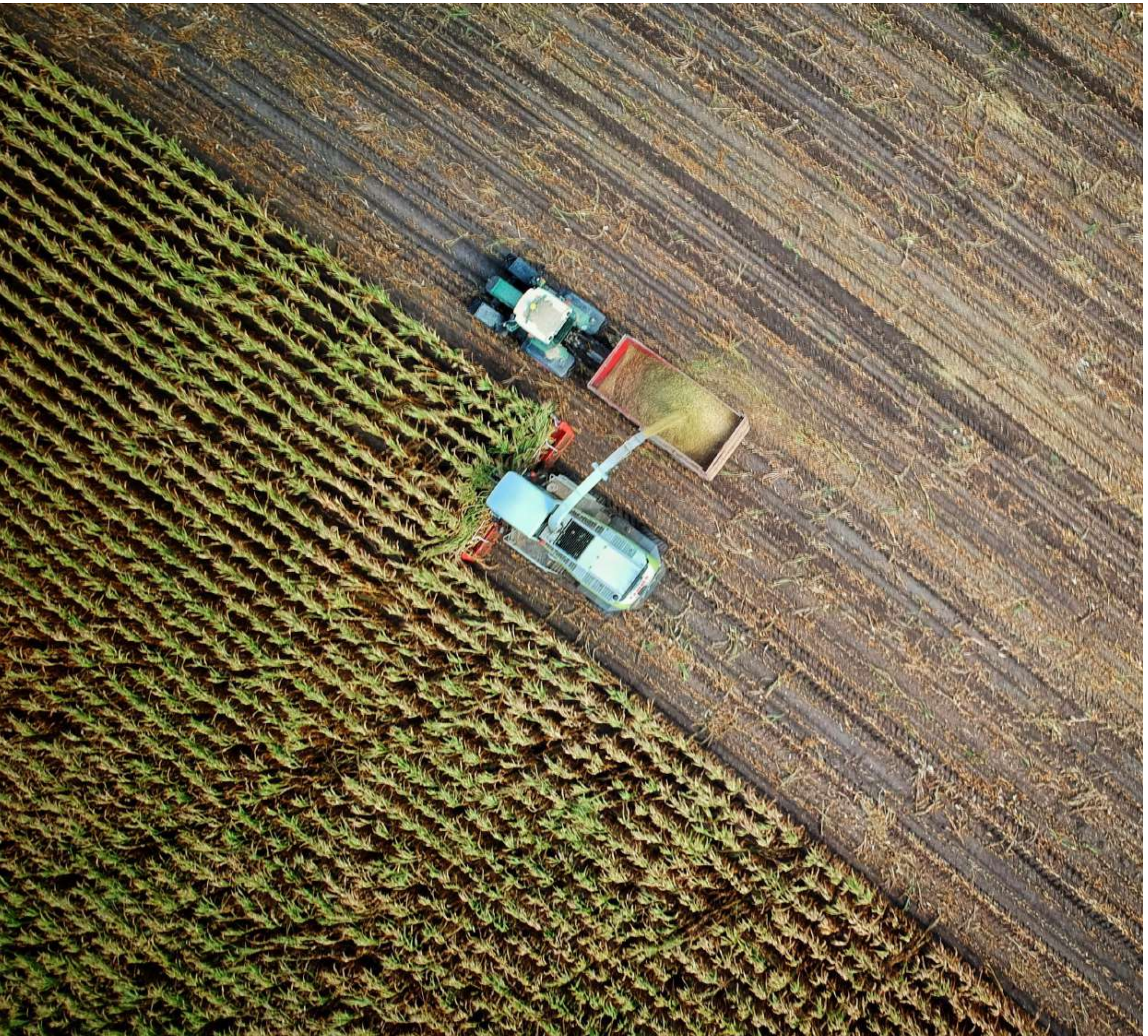
Brands need to be clear about why they need the information they are asking for and what they intend to do with it. Often, brands can be demanding of innovators wanting to see third party LCAs and certifications, treating them just like a new supply chain partner. However, these companies are not at the same stage of development and commercialization as conventional supply chain partners and this should be taken into consideration. Rather than asking for all this information straight away, brands should consider what information they really need to know and whether the information the innovator can share addresses those key requirements. The table above is a useful framework to help facilitate these conversations.

Section 4 of the report explores some of the material development choices that take place throughout the innovation process, including feedstock, chemistry and end of use. The following section explores some of these topics from an impact perspective, as well as including some other potential hotspots:

- Feedstock
- Process
- Chemistry
- Energy
- Water
- Byproducts and waste management
- Product ingredients and performance
- End of use
- Social impact

To dive into some of these in more detail:

IN BIOTECHNOLOGY THE WORD FEEDSTOCK IS MOST COMMONLY USED TO DESCRIBE A NUTRIENT SOURCE; IT IS **AN INGREDIENT THAT IS CONSUMED BY A LIVING ORGANISM** IN A PROCESS SUCH AS FERMENTATION, AND IS THEREFORE NOT INTENDED TO BE PRESENT IN THE FINAL MATERIAL/ PRODUCT.



FEEDSTOCK

"Feedstock" is a term used in industry which, and at its broadest, describes a "material that is used in an industrial process"[61]. This means that a feedstock can both be a component that makes up an end product, or a resource that will be exhausted in the manufacturing process. In biotechnology, the word feedstock is most commonly used to describe a nutrient source, also known as a carbon source for example sugars; it is an ingredient that is consumed by a living organism in a process such as fermentation, and is therefore not intended to be present in the final material/ product. Some examples of different feedstocks include:

- Corn, corn stover, wheat, sugarcane, sugar cane bagasse, potato, sugar beet, rice, plant oil, fruit
- Agricultural waste and residues - e.g wheat straw, wood waste
- Algae
- Greenhouse gases such as carbon oxide and methane
- Other waste residues eg: municipal solid waste

Three tangible examples in materials of how the term "feedstock" can be applied are:

1. **Pinatex**: in Pinatex's process, the feedstock is pineapple leaves (biomass from agricultural waste) that is used to make the final material.
2. **Mycelium "leather"**: in this process the living organism, mycelium, is fed a feedstock (e.g. sugar from a plant source, along with and other nutrients) which it consumes and uses as fuel in order to grow more of itself. Since the mycelium also makes up the final material it can also be classed as a feedstock to the material itself.
3. **Recombinant silk**: in this process living microorganisms, e.g. yeast or bacteria, are supplied a feedstock, (e.g. sugar from corn), which they consume and convert (biosynthesize) into a silk like protein. In this instance, the feedstock (sugar) is exhausted in the process, and the end material is not made of corn or sugar but rather a silk protein.

Different feedstock sources are usually framed in the context of 1st, 2nd, 3rd and 4th generation with an assumption that moving towards 4th generation would always be the ultimate goal. However, this is not always the case as there are other considerations that should be taken into account around process efficiency, energy consumption, existing supply chains and supply chain stability. These feedstocks can have different environmental impacts depending on where they come from and how they are used. Often brands have concerns around the use of feedstocks that are also used as food or feed crops, for example corn or sugarcane. However, challenges can also arise through the use of waste feedstocks that might have also been used as fertilizer or for animal feed.

Therefore, understanding the nuances of these different feedstocks is key, thinking about whether any compromises have been made or what other inputs have been required to produce it - for example pesticides and water as well as where they are being produced. Evaluating all upstream and downstream aspects is fundamental to truly understanding the entire impact of a particular process and how that fits into the overall ecosystem.

It's also important to assess what feedstocks are commercially available now that can help support bio based processes versus future feedstocks that are not yet scaled and require further technical and engineering development work.

CHEMICAL COMPLIANCE

Another important impact hotspot is chemical compliance. The interviewed brands flagged this as a key focus area for them and most brands have a Restricted Substances List (RSL) or Manufacturing Restricted Substances List (MRSL). A restricted substances list targets the chemicals that end up in the final product. These are particularly important to ensure the products are compliant with legislation. However, it doesn't take into account all of the chemicals used in the whole manufacturing process. An MRSL[62]covers this aspect as it provides brands, retailers, suppliers and manufacturers with a framework for the use of restricted substances in chemical formulations commonly used in the raw material and product manufacturing processes. Brands' RSL or MRSL often follow either ZDHC's or Apparel Footwear International RSL Management's (AFIRM) guidelines[63]. ZDHC is a not for profit organisation setup to enable stakeholders in the apparel and footwear industry to implement sustainable chemical management best practice[64]. AFIRM is a global organisation that provides resources for self governing RSL implementation across the apparel and footwear supply chain[65].

A **RESTRICTED SUBSTANCES LIST** TARGETS THE CHEMICALS THAT END UP IN THE FINAL PRODUCT. THESE ARE PARTICULARLY IMPORTANT TO ENSURE THE PRODUCTS ARE COMPLIANT WITH LEGISLATION.

These lists and guidelines are usually available on a brand's website or upon request. One example is adidas' A01 chemical compliance document which is a comprehensive overview of their chemical management practices[66]. Kering also has a number of standards that are available, including a full report outlining standards on raw materials and manufacturing processes[67]. These are all useful resources for innovators to further educate themselves on what levels of compliance are expected. A short summary of, and links to these and additional resources, can be found in the appendix.

When speaking with experts on this topic, they flagged that brands often focus heavily on feedstocks whilst the actual manufacturing process is neglected. Although the MRSL does cover chemical usage throughout the manufacturing process, more effort needs to be attributed to understanding the various chemicals that are being used and assessing the potential hazards of each. This includes considering what byproducts might come out of a production process such as fermentation. Alongside this, materials often require further chemical input and processing steps or, for example, blending with non biobased materials in order to be applied in the fashion industry. These equally need to be taken into account when assessing the overall impact of a material and consequences at end of use.

Brands often ask innovators for certifications such as Bluesign[68] or OEKO TEX[69] too early in their development process. Instead, they could consider asking questions around the guardrails innovators have in place, or to share a list of key chemicals the innovator should stay away from. Innovators can keep track of the chemistry they are using and share this information with their partners. Once they have locked down their process they can then look into certifications. However, it should be noted that innovators will need to comply with REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) legislation (European Union's legislation on chemicals) in order to be able to sell their products there.[70]

For some innovators, chemistry is the most important area of impact and often at the core of the business. Some have developed a set of chemistry principles, including a hierarchy of key assessment areas and ingredients they aim to avoid. One innovator recommended using SciveraLENS which has a stoplight system, making it easy to assess whether a chemical is on an MRSL or not[71].

Accordingly, setting guiding principles and having a clear overview of impact hotspots from the offset enables innovators to use this data to make informed development decisions both internally and where necessary with their partners. However, brands must understand why they are asking for certain chemical certifications and whether they are required considering an innovator's stage of development. Instead it might be more constructive to ask them to share the guidelines or data they have around their key processes and to ask questions to delve into this deeper.

END OF USE

Although a further analysis of the different end of use impacts such as biodegradability and compostability are out of scope for the purposes of this report, it is important to acknowledge the challenges that arise here when developing blended biomaterials. Depending on the type of material, blending biobased and petroleum derived materials can create challenges at end of use that render them neither compostable nor recyclable. It should be noted that biobased products are not automatically compostable and petroleum based products are not automatically non compostable. The chemical structure of the ingredient or material and the physical form are most important when determining whether a product is either or. Greater transparency and understanding around the final material components is required to understand its true environmental impact.

Stakeholders in the supply chain should be thinking about creating products with the end of use in mind, addressing how they can build a circular system and how to fit these materials into that system.

SOCIAL IMPACT

it is common knowledge that the current fashion supply chain has a number of associated issues relating to labour, particularly in raw material extraction and production. Therefore companies should consider and address the potential wider social impacts of scaling these innovations to ensure they do not have a negative social impact, particularly when mapping out what the supply chain will look like at scale.

All the topics covered above are not only important for innovators but for all stakeholders along the supply chain. Generally through our research it was felt that startups in the sustainable innovation space are frequently held to higher standards than conventional supply chain players. It is important for brands to be working with all players throughout the supply chain to drive greater transparency around existing production processes.

Table 3 outlines a list of questions that can be used as a useful resource for brands to understand the nuances of both their upstream and downstream operations. These questions can be asked of all their supply chain partners.

TABLE 3: QUESTIONS FOR BRANDS TO ASK THEIR SUPPLY CHAIN PARTNERS

OVERARCHING	• How does your material/product fit into a circular system?
Feedstock	• What feedstock is being used? Eg: corn, sugarcane, sugarbeet, agriwaste, GHGs • Where does the feedstock come from (geographic region)? • Could the land be used to grow food or feed? • What other options are commercially available today? • What might be potential unintended consequences of scaling up the production of this feedstock? • Are pesticides or fertilisers being used to grow these crops?
Process type	• What processes are being used? (see diagrams above) • Where and how would the innovation fit into existing supply chains? • Does it require any new processes or machinery?
Chemistry	• What chemicals are used in the process? • Are there any byproducts? Are any of these toxic? • How are they recovered, recycled or disposed of? • Are there any chemical compounds used that could impact ecotoxicity or human toxicity? • Are any of the chemicals being used on the Restricted Substances Lists e.g. ZDHC's? ◦ If yes, what is the plan to move away from these? • Have you complied with REACH?
Energy	• What energy source does your process use? • Are you able to track what volumes of emissions are emitted?
Water	• Is wastewater properly treated and processed?
Byproducts and waste management	• Are any byproducts being generated? ◦ If yes - how are these disposed of? • If microorganisms are used (GMO / non GMO), what procedures are in place for safe disposal?
Product ingredients and performance	• Are you using genetically modified organisms or feedstock? • What % of the final product is biobased? • What other materials is it blended with? • What is the source of the bio content? • How durable is the product compared to the material it is replacing? • What coproducts are produced during the production process? • What are these coproducts being used for? Or how are they disposed?
End of Use	• What happens to the material or product at end of use? • Where does it sit on a sliding scale from nonrecyclable to home compostable? • If it biodegrades or composts under what conditions? • What standards or tests have been run to verify this?
Social Impact	• If you are creating a new material: what existing supply chains are you displacing and who will be impacted? • Are there any unintended social impact consequences of using new feedstocks? • Are new jobs or professions created or old ones rendered obsolete? • What level of traceability can you provide?

It is also important for innovators to be able to have an open and transparent dialogue with their partners and ask the brands questions around their sustainability strategies and impact.

See Table 4 for some questions innovators can ask brands on this topic.

TABLE 4: QUESTIONS FOR INNOVATORS TO ASK BRANDS

OVERARCHING	• Do you have a plan or targets around circularity in place? • How can you support the development of products that would fit into that system? • Can you share any impact data you have on current materials or relevant processes? • What are your key impact focus areas as a brand? Eg: what's off limits or highest priority when it comes to impact? • What is your position on genetically modified organisms and their use? • Can you support us with our calculations, data collection and impact tracking?
Feedstock	• Do you have any data or guidelines on preferred feedstocks?
Process type	• Can you connect us with key supply chain partners who can help us with pilot material development and scale up?
Chemistry	• Do you have any restricted substance lists or chemical compliance information we should be aware of? • What are the tests you recommend we prioritise? • Can you offer support with doing these inhouse? • What certifications does your organisation predominantly use eg: OEKO-TEX, Bluesign?
Energy	• Do you have any targets around energy use, source and efficiency in place?
Water	• Do you have any targets around water use and waste water management in place?
Byproducts and waste management	• Do you have any specific standards around byproducts and waste management in place?
Product ingredients and performance	• Do you have a perspective on what % of biobased content needs to be in a finished material?
End of Use	• What is your position on end of use solutions? • What is the end of use profile of similar existing materials in your supply chain? • What are your end of use targets or priorities as an organisation?
Social Impact	• Do you pay the living wage within your supply chain? • Do you have a Code of Ethics and what does it entail?

Image: Courtesy of Made with Reishi™ by MycoWorks

KEY INSIGHTS FOR IMPACT ANALYSIS

In conclusion, there are a number of key insights that help facilitate a more effective development process when it comes to assessing impact. These have been summarized below.

For Innovators:

- Start the process sooner rather than later.
- Set guiding principles based on initial findings.
- Be clear on priorities from the outset, what will you not compromise on eg; using a more hazardous chemical to reduce carbon impact;
- Collect as much data as possible.
- Include all upstream and downstream implications.
- Align with commonly used frameworks or criteria, for example the ISO standards or ZDHC to help more effectively align at scale.

For brands:

- Be clear about why you need this data or what you want to see.
- Share any standards or as much information as you can with innovators from the start.
- Be clear up front on your position as an organisation on key topics eg: the source of raw materials, % of required bio content, desirable end of use solutions.
- Have a clear understanding of why you have that position and understand the nuances of using different feedstocks and chemistries.
- Work with and support innovators to fill data gaps - it shouldn't be solely on them.
- Connect the innovator with service providers you have previously worked with.
- Hold your existing supply chain partners to as high a standard as you do any innovators.

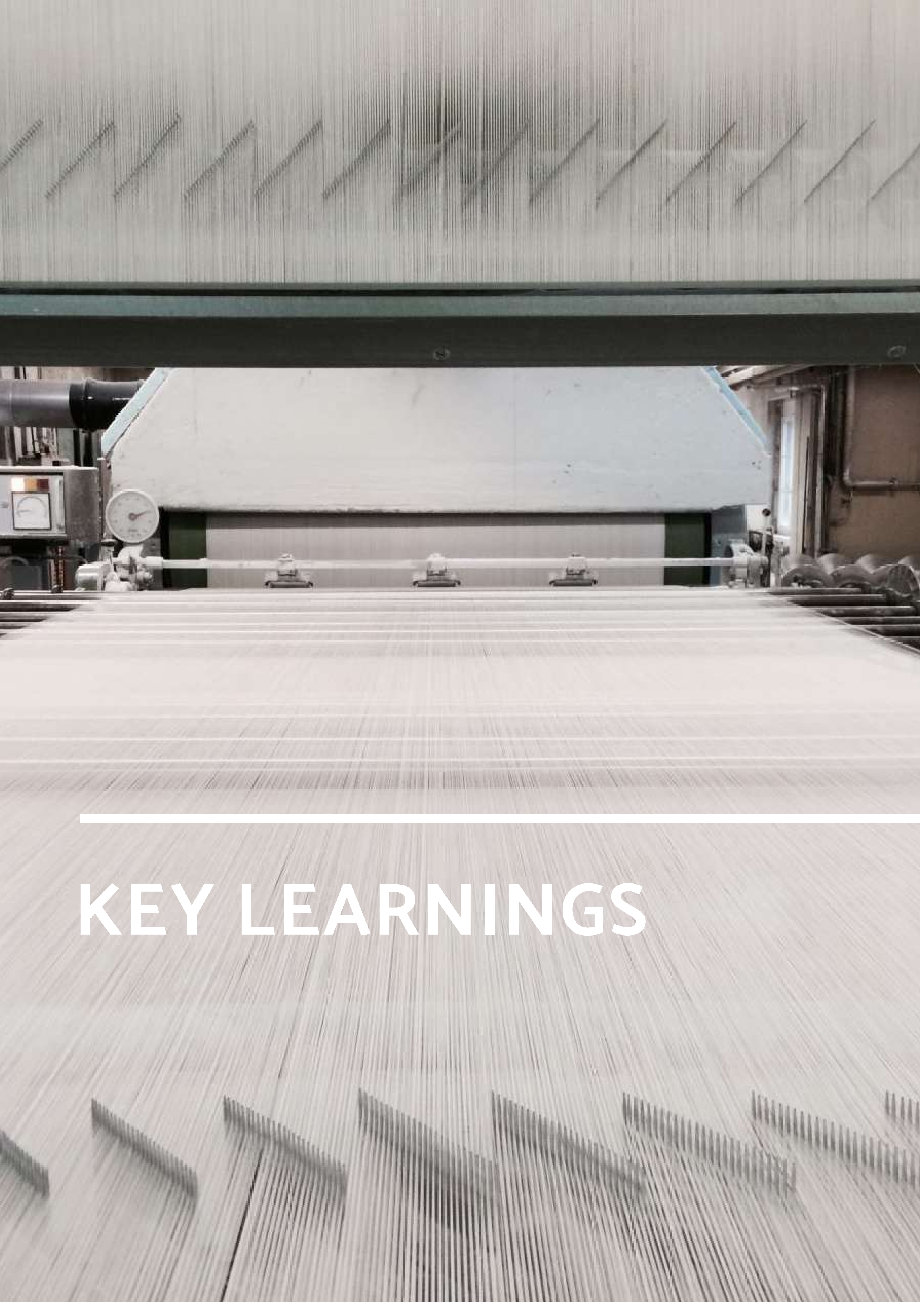
For everyone:

- Be open and transparent, especially regarding potential pitfalls and current deficiencies - ideally with concrete plans how to tackle these.
- If necessary, work together to develop a plan to move towards more sustainable processing or feedstocks.
- Be transparent on the needs: when do companies need which deliverable, and why? When startups can deliver which deliverable, and why?
- Differences in results for modeling "technology at lab scale" and "technology scaled up": higher impacts at lab scale (vs existing scaled up technologies) are normal.
- Consider how to communicate and position your technology at that stage for startups, and how to interpret this information as a company.

Useful insights for conducting LCAs:

- Utilise the table above to understand what level of LCA is needed at different stages of a company's development.
- Align with existing methods of impact assessment for example the ISO standards (ISO 14040 and 14044).
- Provide an overview on the range of deliverables possible within the LCA.
- Attach examples of these deliverables so people can have a look at the outcome.
- List their respective use cases (what can be done with this deliverable?), limitations (what cannot be done with this deliverable?) and resources needed.
- Find the right service provider.

Images:
L: AMSilk, Biosteel®
B: Bolt Threads



KEY LEARNINGS

THERE WERE SOME COMMON THEMES THROUGHOUT THE INTERVIEWS PARTICULARLY AROUND **QUESTIONS BRANDS AND INNOVATORS CAN ASK EACH OTHER TO SUPPORT PARTNERSHIP DEVELOPMENT.** KEY HIGHLIGHTS HAVE BEEN SUMMARISED HERE.

Images:
L: LAUSCHSICHT / QWSTION
R: PILI Bio

KEY LEARNINGS

There were some common themes throughout the interviews, particularly around questions brands and innovators can ask each other to support partnership development. Highlights are summarized below:

For Innovators

- **Transparency** - be transparent and honest about development timelines.
- **Milestones** - set realistic milestones and deliverables, don't overpromise.
- **Impact** - identify your impact hotspots early on and adjust accordingly.
- **Process** - be prepared to answer questions about feedstocks, process, chemistry and end of use.
- **Team** - build a diverse team; technical, commercial, design and product development.
- **Partnerships** - be clear on how the brand can best contribute.

For Brands

- **Performance** - share your quality and performance goals.
- **Supply Chain** - connect innovators to your key supply chain associates and ecosystem partners.
- **Guardrails** - be clear on your own guardrails especially relating to sustainability goals ie; feedstocks and end of use.
- **Patience** - be patient and mindful of the time and complexity of material development.
- **Milestones** - set realistic milestones and deliverables.
- **Commitment** - demonstrate long term commitment (including financial) to bring material to scale.
- **Tolerance** - be transparent about your tolerance on key aspects e.g. price in the short, medium and long term.

For Both

- **Goals and milestones** - establish goals together up front regarding intent, scope of work and timelines.
- **Partnerships** - jointly define and build a strong partnership to allow transparency about progress.
- **Consortia** - consider what makes the most effective model to bring disruptive sustainable solutions to scale.
- **Performance** - align on main priorities and key metrics.
- **Definitions** - align on definitions of e.g. scale and TRL as these can deviate for both parties.
- **Timing** - think carefully about when is the right time to engage to avoid project fatigue.
- **Exclusivity** - be mindful about balancing exclusivity vs growth.
- **Roadmap to scale** - identify key supply chain partners and how to scale vs. proof of concept.
- **Compromise**: finding a middle ground and shared values on how to create products that fit both party's needs.

What is generally evident from the research and interviews is that the key to successful collaboration is a partnership that nurtures, facilitates and rewards long term strategic thinking and codevelopment, as well as shared knowledge and resources.

Image:
Evolved by Nature

TABLE 5: KEY LEARNINGS - QUESTIONS FOR INNOVATORS AND BRANDS

While more specific questions and learnings around impact hotspots are covered in section 5 above, below are some key questions that are useful for both innovators and brands alike.

CATEGORY	QUESTIONS FOR BRANDS TO ASK INNOVATORS	QUESTIONS FOR INNOVATORS TO ASK BRANDS	FOR BOTH
Roadmap to scale & Scaling	● How can we support you with your roadmap to scale?	● What information can we provide to help establish mutually agreed, realistic KPIs, deliverables and milestones?	● How do we define scale and TRL levels? ● What are the steps from proof of concept to scale?

R&D	● What type of support and feedback can we provide analyzing your material
	  ● Are there any performance metrics of comparable conventional materials we can share?
	● How can our supply chain manufacturing partners provide support?
	● How can we assist you with an understanding of requirements for manufacturability?
	● Who in our company has the best suited technical background to support you?
		● Do you have technical expertise in house e.g. a dedicated team or expert who will work with us on our technology and product development?
		● When is the right time to involve design and product development teams, e.g. light touch consulting early on, then continue with the innovation team until further along?
		● Can you share any performance metrics?
		  ● What test data, SOPs, standards or guidelines can you share with us?
			● What are our priorities and key metrics?

Scaling	● How can we support with pricing information? ● Can we connect you with the right experts within our organisation (or supply chain)? ● How can we support you with marketing activities?	● What kind of financial or in kind development support can you provide? ● Can we discuss cobranding?	● What are the shared values that fit both our needs? ● How do we align our vision from a marketing angle and tell a story together?
Partnering	● Which other partnerships would be additive for us to leverage?	● Can you connect us with your key (supply chain) partners? ● Who would be our constant project partner/internal organisational champion for the duration of our relationship?	● How do we define a successful partnership?
Material development choices	● See questions listed above in Section 5 Impact	● See questions listed above in Section 5 Impact	● What key impact metrics do we focus on? ● What are we benchmarking this against? ● Do we need to get any third party certifications? ● If yes - at what stage and is this crucial?

OPPORTUNITIES FOR FURTHER RESEARCH

There were some topics that this report has not had the opportunity to explore in depth which urgently need addressing by the industry for the better understanding of all involved:

FEEDSTOCKS

A topic that arose during the interviews and throughout the research process was around the environmental impact of different feedstocks. Frequently feedstocks are classed into different "generation" ranging from first to fourth, with a transition away from first generation being the optimum goal. However, through our research and speaking with other industry stakeholders such as the Textile Exchange Biosynthetics working group, it became clear that the nuances of different feedstocks and their impacts are complex. It is dependent on where the feedstock is coming from, where its being grown, whether it is commercially available and how its being processed. Often waste feedstocks are not yet commercially available and require more development work. Further research is needed on this topic to better understand the trade off between energy efficiency and environmental impact.

GENETICALLY MODIFIED ORGANISMS

The use of genetically modified organisms (GMOs) is a topic that came up during the interviews and is often widely discussed within this space. Concerns may be raised around the use of GMOs in the production of new materials, chemicals and dyestuffs. This concern often centers on the use of a genetically modified organism in a bioreactor, or it can surface in relation to understanding impacts of different types of feedstock being fed to an organism, which, for example, could be sugar from a GMO crop. Sensitivities can vary quite significantly depending on geography; the topic seems to be much more contentious in Europe where GMOs are less common. In the US, GMOs have been widely used for many years in both agriculture and industrial biotechnology to produce everything from cotton, enzymes for washing powders, to insulin.[72] This is an area that requires further research and understanding, particularly to address concerns and challenges different stakeholders face and how these can be mitigated.

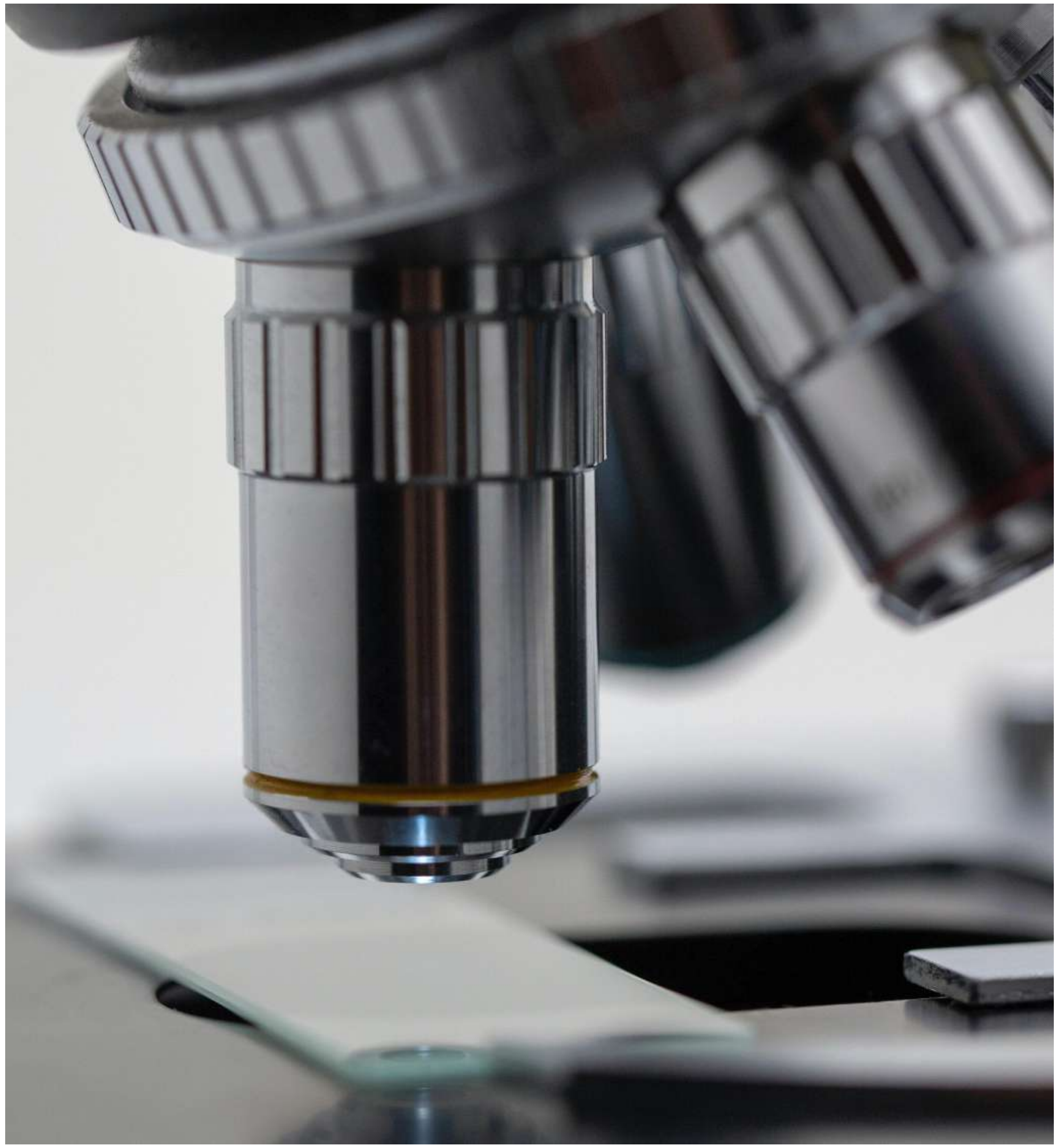
END OF USE

In the interviews and our wider experience working in this space, it is evident that there is still a lack of clarity around the different end of use options and the impact from an environmental perspective. This includes terms such as biodegradable, compostable, industrially compostable, home compostable, marine degradable etc. Please see the glossary for high level definitions of these terms.

Although country specific standards for home composting exist there are no international standards that cover this topic. There are also a lack of consistent standards to assess marine degradability which makes it challenging for innovators and brands to properly assess the impact of materials in this space. Further research is needed on this topic.

QUANTIFIABLE SUSTAINABILITY ASSESSMENT

This report provides an overview of key insights and considerations when assessing impact hotspots of new biomaterials. It does not dive into or assess the actual impact of any of these processes or innovations. In short the report concludes that it is complicated to measure impact and even more challenging when these solutions are yet to scale. There is no simple answer that one material is better than another, it is too nuanced and complex to arrive at such conclusions. Readers should be mindful of this when assessing different innovations and solutions and look to best understand what their priorities are and what they can do to reduce their impact.



THE FUTURE OF THE FIELD

NATURE'S MATERIALS; COTTON, WOOL, SILK, CASHMERE, LEATHER ETC ARE PRIZED BECAUSE THEY MEET SO MANY NEEDS; COMFORT, DURABILITY, AND TRANSFORMATIVE POSSIBILITIES, ALL DELIVERED AT **PRICES THAT REFLECT CENTURIES OF INDUSTRIAL EFFICIENCY.**

Images:
L: Biofabricate Summit 2019, Brewed Protein™ spun yarn woven fabric samples, Spiber, photo by Chloe Hashemi
R: AMSilk/ OMEGA NATO, Biosteel®

TIME & COMPLEXITY

As we have established in this report, biomaterials are a broad category covering many different technologies. Biofabricated materials, leveraging the tools of biotechnology, are both the most novel, but also the most technically challenging - requiring mastery of biological production with predictable, consistent quantities and qualities before even beginning further transformation into fibers, fabrics or sheet materials.

Added to this is the expectation that, for the most part, they will "drop in" to existing textile and product manufacturing infrastructure - setting a high bar for first generation "challenger" materials. There is much new ground to be broken and so many technical hurdles to overcome along the way. Hence the longest timeline to go from concept to scaled commercial production: currently around 10-15 years would appear to be the norm. Those that have come to market thus far, e.g. "recombinant silk" from the likes of AMSilk and Spiber are both the result of over a decade of research, millions of USD$, and teams with experienced biotech founders.

Many brands have begun their journey in this space but challenges around financing have slowed the pace of change. The industry is reliant on the development of these new disruptive solutions to accelerate the transformation to sustainable circular practices. However, too many innovators still fail to receive the support needed from stakeholders within the ecosystem including brands, investors and supply chain partners. The industry must collaborate to actively engineer the conditions for these innovators to succeed.

The good news is that the last 5 years has seen an exponential growth of material innovation tackling biological alternatives to fossil fuel, plant and animal; dyes, chemicals, fibers, fabrics, and leather alternatives. There is more awareness amongst investors and brands alike of the coming wave of consumer biotech solutions made possible by synthetic biology and biodesign tools. More capital is available, more partnerships are opening up, and more consumers are demanding sustainable alternatives.

EXPECTATIONS

These new technologies are not yet "silver bullets" however. Nature's materials; cotton, wool, silk, cashmere, leather etc are prized because they meet so many needs; comfort, durability, and transformative possibilities, all delivered at prices that reflect centuries of industrial efficiency. High performing manmade synthetics, based on cheap fossil fuel, have also raised our expectations of material innovation to encompass properties beyond those offered by nature; super stretch, color saturation and fastness, performance finishes, extreme durability and so forth.

The challenge for innovators is in understanding deeply what the customer is looking for today and then how to walk towards that, acknowledging that the first generation of their product will likely not be the best; each iteration will bring improvements. The challenge for brands is how to walk with innovators on that journey, finding ways to support development so that technical gaps can be closed (or compromises found) in the short term in order to achieve greater success in the long term.

History teaches us that material innovation is a constant journey of iteration and improvements. It took DuPont ten years to create lycra, a further three to bring it to market, but 60 years later the material still continues to evolve and improve.

Image: Biofabricate Summit 2019, MOON PARKA by The North Face Japan (GOLDWIN Inc.) & Spiber, photo by Chloe Hashemi

Some of the first pioneers of biofabricated materials might (off the record) admit they thought they would get to commercial product faster than they have. It's a balancing act of not really knowing at the outset how long scientific discovery, technical iteration, and scaling will take (no one has ever operated their exact process before), contrasted with satisfying what investors want to hear regarding expected timeframes for a return on investment (ROI).

Equally, certain brands who were quick to engage with innovators early in their journeys might also admit they have had to adjust their expectations both in terms of timelines but also product performance, aesthetic or price. Creating new to the world materials is not like writing an app, it is measured in multiple years not months. Many will have to pivot technology or product or both along the way. It is therefore not realistic for the fashion industry to expect overnight replacements to materials which have had properties, volume and price optimized over many many years even after launching to market.

We should also caution against unintended consequences. The drive for "more sustainable" replacements can lead to material innovation that has not carefully considered the full implications of a particular technology or process in a holistic manner. While brands are eager to find alternative materials, it would be disastrous if the push for rapid innovation led to those same efforts creating a new generation of harmful products. All aspects of a new material need to be factored before mass adoption if we are to avoid unforeseen environmental issues down the line. End of use should be the first consideration not the last.

As the next wave of innovators attempt to solve similar problems, they can greatly learn from the mistakes of those who went there first. Mentoring and sharing of collective learnings would prevent entrepreneurial and development errors being made over again.

THE CHALLENGE FOR INNOVATORS IS IN UNDERSTANDING DEEPLY WHAT THE CUSTOMER IS LOOKING FOR TODAY AND THEN HOW TO WALK TOWARDS THAT, ACKNOWLEDGING THAT THE FIRST GENERATION OF THEIR PRODUCT WILL LIKELY NOT BE THE BEST; EACH ITERATION WILL BRING IMPROVEMENTS.

AVAILABILITY & LONG TERM PROSPECTS

As mentioned in the partnering section, with most new technologies the first time they show up is often in severely limited quantities at a high cost. But just as with other technologies, economies of scale will bring down prices over time. Biofabricated materials, in almost all instances, will sell at premium/high cost for the foreseeable future. Brands at the mass or lower end of the market will likely have to be more patient to access these material innovations for their customers.

As the diagram section and definitions attest, the field of "biomaterials" encompasses radically different technologies with vastly different times to market. The purpose of this report is to help distinguish these relative complexities and to contribute understanding about why biofabricated products in particular take considerably longer to develop and scale, but as they do will usher in a new era of material innovation with properties and impacts improving upon those we have today. The promise of synthetic biology, ultimately, is not that biology is directly copied (biomimicry), rather, by understanding how to design and engineer with nature's building blocks, it will be possible to efficiently tune the properties that are required. Many of the companies featured in this report are pioneering the foundations of material innovation that will have us rethinking materials for decades to come.

A FINAL NOTE TO THE INDUSTRY

While fashion brands may desire a black and white answer to the question "which is the most sustainable material or process?" unfortunately it's not possible to hold up any one process as "better" than another when there are so many potential variables in each system. Many materials can be described as biomaterials, but the "bio" prefix masks underlying differences in technologies, complexity, and potential impacts. All 'biomaterials' are not the same.

Image: Courtesy of Made with Reishi™ by MycoWorks

Whatever innovators or brands call their technologies and materials, and how much the consumer cares or understands about what those terms mean, it is not safe to assume that "bio" = better. When dealing with any material production process, it's important to go deeper and seek to understand what the inputs and outputs are, how something is made, and what the potential impacts might be.

MANY MATERIALS CAN BE DESCRIBED AS BIOMATERIALS, BUT **THE "BIO" PREFIX MASKS UNDERLYING DIFFERENCES IN TECHNOLOGIES,** COMPLEXITY, AND POTENTIAL IMPACTS. ALL 'BIOMATERIALS' ARE NOT THE SAME.

There is still much work to be done understanding the relative impacts of different technology approaches along with thinking about how to even classify some of these new emergent products. Where should these new materials sit in relation to the established textile classification system? What about leather - which does not sit in that classification? Are these new biomaterials "natural"or "manmade"?, or are they "manmade naturals"? or something else entirely that requires a new classification? What do they mean for regulatory classification (and associated tax tariffs)? Clearly many questions have yet to be answered. It will require the fashion industry coming together with innovators, industry groups and possibly regulators to establish guidelines and standards that can be broadly agreed upon and adopted.

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GLOSSARY

Algae: Algae are a diverse group of aquatic organisms. They can exist as single microscopic cells (microalgae), they can be macroscopic or multicellular; live in colonies; or have a plant like structure, as is with giant kelp. All grow through ability to conduct photosynthesis whereby sunlight, CO_2 and a few nutrients, including nitrogen and phosphorous are converted into a material known as biomass.

Bacteria: Bacteria are single-celled microorganisms. They are found almost everywhere on Earth and are vital to the planet's ecosystems. Some bacteria cause diseases, these are called pathogenic, but there's also good bacteria. In the gut of our digestive system we have bacteria that are necessary to help our bodies function in a normal way. We have 10 times more bacterial cells than we have human cells. The biotechnology industry uses bacterial cells for the production of biological substances that are useful to human existence, including fuels, foods, medicines, hormones, enzymes, proteins and more.

Bio: In english the word 'bio' is connected with life and living things. 'Bio' is often used as an abbreviation for the noun 'biology' or the adjective 'biological'. 'Bio' is problematic in French, for example, as the word means 'organic' which is not necesarily the same thing.

Biobased: The term biobased product refers to products wholly or partly derived from biomass, such as plants, trees or animals (the biomass can have undergone physical, chemical or biological treatment).The product can be an intermediate, material, semifinished or final product. NB: bio-based does not equal biodegradable. The property of biodegradation does not depend on the resource basis of a material but is rather linked to its chemical structure. In other words, 100% bio-based plastics may be non-biodegradable, and 100% fossil-based plastics can biodegrade.

Biobased content: Fraction of a product that is derived from biomass.

Bioinspired: The development of novel materials, devices, and structures inspired by solutions found in biological systems and biological evolution and refinement which has occurred over millions of years.

Bioinspired materials are synthetic materials whose structure, properties or function mimic those of natural materials or living matter. Examples of bioinspired materials are light-harvesting photonic materials that mimic photosynthesis, structural composites that imitate the structure of nacre, and metal actuators inspired by the movements of jellyfish.

Biodegradable: Biodegradation is the degradation of the materials into environmentally acceptable products such as water, carbon dioxide, and biomass by the action of naturally available microorganisms under normal environmental conditions.

Bioderived: Derived from biological sources.

Bioeconomy: The biological sciences are adding value to a host of products and services, producing what some have labelled the "bioeconomy". From a broad economic perspective, the bioeconomy refers to the set of economic activities relating to the invention, development, production and use of biological products and processes.

Biogenic: Produced in natural processes by living organisms but not fossilized or derived from fossil resources.

Biogenic carbon: Biogenic carbon is the emissions related to the natural carbon cycle, as well as those resulting from the combustion, harvest, digestion, fermentation, decomposition or processing of biologically based materials.

Biomanufacture: The process of using living systems, particularly microorganisms and cell cultures, to produce biological molecules and materials on a commercial scale.

Biomass: Raw material of biological origin excluding material embedded in geological formations or transformed to fossilized material.

Biomimicry: Biomimicry is a practice that learns from and mimics the strategies found in nature to solve human design challenges. Famous examples of applied biomimicry in design and engineering are the Japanese Bullet train (modeled on a kingfisher bird) or Speedo swimsuits (modeled on sharkskin). The application of biomimetic principles does not imply a material or process is of biological origin.

Bioplastic: Bioplastics are not just one single substance, they comprise of a whole family of materials with differing properties and applications. According to European Bioplastics, a plastic material is defined as a bioplastic if it is either bio-based, biodegradable, or features both properties. The term "bioplastics" is actually used for two separate things: biobased plastics (plastics made at least partly from biological matter) and biodegradable plastics (plastics that can be completely broken down by microbes in a reasonable timeframe, given specific conditions). Not all biobased plastics are biodegradable, and not all biodegradable plastics are biobased. And even biodegradable plastics might not biodegrade in every environment.

Bioreactor: An apparatus for growing microorganisms such as yeast, bacteria, or animal cells under controlled conditions. Bioreactors are used industrially to manufacture many products including enzymes, food additives, chemicals, and other products. Bioreactor and fermentor are two words for basically the same thing. Scientists who cultivate bacteria, yeast, or fungi often use the term fermentor. The term bioreactor often relates to the cultivation of mammalian cells but is also generically used. Broadly speaking, bioreactors and fermentors are culture systems to produce cells or organisms. (see also fermentation)

Biosynthesis: The production of a complex chemical compound from simpler molecules in a living organism. There are multiple types of biosynthesis - one example is photosynthesis - where sunlight, CO_2 and water are converted into food for a plant to grow. Biosynthesis occurs throughout the natural world, in plants, in microorganisms, in animals.

Carbon: Carbon is a widely distributed element that forms organic compounds in combination with hydrogen, oxygen, etc. These carbon-based molecules are the basic building blocks of humans, animals, plants, trees and soils. Some greenhouse gases, such as CO_2 and methane, also consist of carbon-based molecules, as do fossil fuels, which are largely made up of hydrocarbons (molecules consisting of hydrogen and carbon).

Compostable, home: Materials suited to be composted in home compost heats (not disposed of in the natural environment) at ambient temperature, rather than high temperature. There are no current international standards but two national standards - French standard NFT 51-800 Australian standard AS 5810 by which home compostability can be assessed.

Compostable industrially: In this process, the material is composted to forum at higher temperatures (50-60oC) in large scale specialized facilities, under controlled conditions57. To be called this it must meet a standard such as EN 13432, EN 14995, ASTM D6400 or ASTM D6868. In addition to breaking down and biodegrading under these conditions, it must also pass additional ecotoxicity tests to show that is does not break down into or release harmful chemicals.

Culture/culturing: The cultivation of bacteria, tissue cells, etc. in a growth medium containing nutrients.

DSP [downstream processing]: Downstream processing (DSP) describes the series of operations required to take biological materials such as cells, tissue culture fluid, or plant tissues, and derive from them a pure and homogeneous protein product.

Environmental Product Declaration (EDP): An Environmental Product Declaration (EPD) is an independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impact of products. As a voluntary declaration of the life-cycle environmental impact, having an EPD for a product does not imply that the declared product is environmentally superior to alternatives.

Fermentation: The chemical breakdown of a substance by bacteria, yeasts, or other microorganisms, typically involving effervescence and the giving off of heat.

GMO: Genetically modified organism. This is a plant, animal, microorganism or other organism whose genetic makeup has been modified in a laboratory using genetic engineering technology. This creates combinations of plant, animal, bacterial and virus genes that do not occur in nature or through traditional crossbreeding methods.

Hyphae: A strand of the threadlike mycelial tissue of fungi.

Lab grown: The term 'lab-grown' has been widely used in the media to describe everything from meat to diamonds. It is often a stand-in term to indicate technologies that are new to certain sectors, for example the use of biotechnology to grow materials for fashion. While early-stage research and development takes place in labs, it is not an accurate term since scaled production, be it food or fashion, is not manufactured in a laboratory. Validated technologies are subsequently transferred to industrial facilities for pilot and then commercial production. Therefore 'lab-grown' is not a term used by most innovators themselves.

Marine degradable: Currently certified by TUV Austria to the ASTM D7081 (but technically withdrawn – there is a newer ASTM D669158 standard) standard – the material must degrade by 90% within 6 months. The lack of consistent standards to assess marine degradability is still an issue, especially since marine degradability is still a developing category – the trade-offs and benefits are not widely understood at present.

Microorganism: A microorganism or microbe is a microscopic organism, which may be single-celled or multicellular. The microbes most commonly associated with the production of materials for consumer textiles include yeast, bacteria, fungi and algae.

Mycelium: The vegetative part of a fungus, consisting of a network of fine white filaments (hyphae). The non-fruiting part, or root system of a mushroom.

Natural: A definition of natural is 'existing in or caused by nature; not made or caused by humankind.'
In the fashion and textile world, 'natural' fibers, fabrics and dyes generally are understood to be obtained directly from an animal or plant. Examples would be, respectively, wool, leather, and fur, cotton, hemp, indigo and saffron.

Organic (chemical compound): Any of a large class of chemical compounds in which one or more atoms of carbon are covalently linked to atoms of other elements, most commonly hydrogen, oxygen, or nitrogen. The few carbon-containing compounds not classified as organic include carbides, carbonates, and cyanides.

Organic (farming): Relating to, yielding, or involving the use of food produced with the use of feed or fertilizer of plant or animal origin without employment of chemically formulated fertilizers, growth stimulants, antibiotics, or pesticides

Petrochemicals: Petrochemicals are chemicals derived from petroleum or natural gas.

Protein: Proteins are biological polymers composed of amino acids. Examples of natural protein biopolymers are silk and collagen.

REACH: Registration, Evaluation, Authorisation and Restriction of Chemicals is a European Union regulation which addresses the production and use of chemical substances, and their potential impacts on both human health and the environment.

Recombinant DNA: Genetically-engineered DNA molecule formed by splicing fragments of DNA from a different source or from another part of the same source, and then introduced into the recipient (host) cell

Renewable carbon: Renewable carbon entails all carbon sources that avoid or substitute the use of any additional fossil carbon from the geosphere.

Synthesis: Chemical synthesis, the construction of complex chemical compounds from simpler ones. Synthesis also enables chemists to produce compounds that do not form naturally for research purposes. In industry, synthesis is used to make products in large quantity.

Synthetic: Pertaining to compounds formed through a chemical process by human agency, as opposed to those of natural origin.

Synthetic biology: Synthetic biology or 'synbio' is an emerging field of research that combines elements of biology, engineering, genetics, chemistry, and computer science. It joins the knowledge and techniques of biology with the practical principles and techniques of engineering. Researchers and companies around the world are using synbio to solve problems in medicine, manufacturing and agriculture. Synthetic biology aims to design and engineer biologically based parts, novel devices and systems as well as redesigning existing, natural biological systems. In synthetic biology, scientists typically stitch together long stretches of DNA and insert them into an organism's genome. These synthesized pieces of DNA could be genes that are found in other organisms or they could be entirely novel.

The Cartagena Protocol: The Cartagena Protocol on Biosafety to the Convention on Biological Diversity is an international treaty governing the movements of living modified organisms (LMOs) resulting from modern biotechnology from one country to another. It was adopted on 29 January 2000 as a supplementary agreement to the Convention on Biological Diversity and entered into force on 11 September 2003.

Tissue-engineering: Tissue engineering (TE) is a rapidly evolving discipline that seeks to repair, replace or regenerate tissues or organs by translating fundamental knowledge in physics, chemistry and biology into practical and effective materials, or devices and clinical strategies

White biotechnology: White biotechnology is a term that is now often used to describe the implementation of biotechnology in the industrial sphere. Biocatalysts (enzymes and microorganisms) are the key tools of white biotechnology, which is considered to be one of the key technological drivers for the growing bioeconomy. Biocatalysts are already present in sectors such as the chemical and agro-food industries, and are used to manufacture products as diverse as antibiotics, paper pulp, bread or advanced polymers.

Yeast: A microscopic fungus consisting of single oval cells that reproduce by budding, and are capable of converting sugar into alcohol and carbon dioxide.

APPENDIX

A. BIOFABRICATION REPORT SURVEY

1. How do you define your material?
   (choose: biobased, biomaterial, biosynthetic, biofabricated, bioassembled, other)

2. Why?

3. How do you define your technology?
   (choose: synthetic biology, biofabricated, grown, other)

4. To have the word 'bio' in the name of the material, what percentage of biological input do you believe it should have?

5. How long has it taken you, or do you believe it will take you, to go from initial proof of concept to a bench scale prototype to pilot scale prototype to a commercial scale prototype?

6. What do you look for in a brand partner? Eg an understanding of dev. time, a commitment to part finance research, pay for exclusivity, use of material brand etc?

7. What are some of the challenges you've encountered in working with brand partners?

8. What questions do you wish a brand would ask?

9. What are the main areas of misunderstanding with a brand?

10. How do you make choices around the materials and chemistries you use?

11. How much have these types of decisions been driven by you partners vs. you values/ the technology dictating it?

12. Do you have your own internal RSL or do you follow those of your partner's or other legislative bodies to guide you in your decision making?

13. How do you make decisions around material compromises eg. performance vs. aesthetic vs. price vs. sustainability? (tensions and trade-offs)

14. Do you have an MVP mindset - if so what does that for you and how does it translate into your financial goal for your first gen product?

15. Have you engaged in any impact assessments, either internally or externally, to date?
    (choose: yes-internally, yes -externally, no)

16. If yes - how has it informed your material development/R&D? Did you share your learnings with brand partners or was it for internal R&D learnings only?

17. If no, how do things like end of life, waste management or other factors inform development?

18. When do you think is the right time for material start-ups to engage in an impact assessment?

19. What would you say are the key impact hotspots you have to consider or take into consideration when developing your material application? Will these shift or have they shifted as you scale up production?

20. What feedstock do you use and what dictated that choice?

21. What would be beneficial education for brands around feedstocks?

22. What chemicals are you using in your process? Are they certified by ZDHC or similar organisation?

B. QUESTIONS FOR INNOVATORS

DEFINITIONS - These definitions are a jumping off point, not agreed definitions

How do you define your material and why?

E.g. biobased, biomaterial, biofabricated?

Do you agree or disagree with the definitions set out in the pre-read? (Biobased USDA)

How do you define your technology? E.g. synthetic biology, biofabricated, grown etc.

To have the word 'bio' in the name of a material what percentage of biological input should it have?

R&D

How long has it taken you to go from initial proof of concept to a bench scale prototype to a pilot scale prototype to a commercial scale prototype?

PARTNERSHIPS/ PAIN POINTS/ LEARNINGS

What do you look for in a brand partner?

E.g. an understanding of dev. time, a commitment to part finance research, pay for exclusivity, use our material brand etc.

What are some of the challenges you've encountered in working with brand partners?

E.g. ability to demonstrate progress when perhaps it's only visible in data rather than visibly or haptically.

What questions do you wish a brand would ask?

What are the main areas of misunderstanding with a brand?

DEVELOPMENT DECISIONS

How do you make choices around the materials and chemistries you use

How much have these types of decisions been driven by your partners vs. your values/ the technology dictating it?

Do you have your own internal RSL or do you follow those of your partner's or other legislative bodies to guide you in your decision making?

Are there any regulations/ industry standards or guidelines that you currently subscribe to?

How do you make decisions around material compromises E.g. performance vs. aesthetic vs. price vs. sustainability? (tensions and trade-offs)

Do you have an MVP mindset – if so what does that mean for you and how does it translate into your goal for a first gen product?

Follow up ?: How quickly would you be looking to get to a gen 2 product?

What trade offs have you had to make as you have scaled up? Any key learnings you would like to share or things that have evolved?

IMPACT ASSESSMENTS

Have you engaged in any Impact assessments, either internally or externally, to date?

Follow up ?: If yes, how has it informed your material development/ R&D?

Follow up ?: If internal – did you share the learnings with brand partners or was it for internal R&D learnings only?

Follow up ?: If no, how do things like end of life, waste management or other factors inform development?

When do you think is the right time for material start-ups to engage in an impact assessment?

How have you walked a line with brands who want the information sooner than is feasible?

What would you say are the key impact hotspots you have to consider or take into consideration when developing your material application? Will these shift or have they shifted as you scale up production?

FEEDSTOCK

What feedstock do you use and what dictated that choice? E.g. best fit for tech, aligned with sustainability values, local abundance etc.

Have you had conversations with brands about your feedstock? If so what were their concerns – what did you learn?

What would be beneficial education for brands around feedstocks?

C. QUESTIONS FOR BRANDS

DEFINITIONS

Does your understanding/ definition of the terms biobased, biomaterial, biosynthetic and biofabrication differ from those provided in the pre-reading materials?

If you already use any of these 'bio' terms, which ones and why?

Do you use them when communicating to your customers?

If so, how do you use them? Have you received any feedback?

To have the word 'bio' in the name of a material what percentage of biological input do you believe it should have?

R&D

How long are you willing to wait from initial proof of concept from an innovator to a bench scale prototype to a pilot scale prototype to a commercial scale prototype?

Have you gotten involved in R&D in a significant way with a start-up in this space?

PARTNERSHIPS/ PAIN POINTS/ LEARNINGS

What do you look for in a material innovation partner?

E.g. a TRL level of 'x' or above, exclusivity, amount of 'bio' content etc.

What are the top things you ask, or focus on, when looking to partner with innovators in this space?

If you have already worked, or engaged, with a material start-up what are some of the challenges you've encountered to date?

(If applicable) What do you find have been the main areas of misunderstanding with a material start-up?

What internal challenges have you faced in terms of lack of understanding around these types of innovations and their long term scalability/ impact within your organisation?

MATERIAL DECISIONS

How do you make choices around the materials you use? How has this changed/is changing?

Are there any regulations/ industry standards or guidelines that you currently subscribe to when choosing materials or chemistries?

Do you have your own internal RSL or do you use other legislative bodies to guide you in your decision making?

Is there any tolerance around compromising on material attributes e.g. performance vs. aesthetic vs. price vs. sustainability? (tensions and trade-offs)

LCA/IMPACT

Have you engaged in any impact/LCA processes, either internally or externally, with a material innovator to date?

Follow up ?: If yes, what were the key learnings from that process?

When do you think is the right time for material start-ups to engage in an impact assessment/ LCA?

Have you had conversations with innovators about the feedstocks they use? If so what are your concerns and how did the innovators address those concerns?

USEFUL RESOURCES

KEY STANDARDS:

A few of the most widely applied and recognized standards and guidelines in the fashion industry include:

- AFIRM: Restricted Substance List for Apparel and Footwear
- Biobased content guidelines of the USDA and the European Committee for Standardization
- DIN CERTO certification body of TUV Rheinland Group
- IEA Bioenergy 'Standards and Labels related to Biobased Products'
- Cradle to Cradle: assesses product safety to humans and the environment, as well as product design for material reuse
- Bluesign certification: combines aspects of consumer safety, water and air emissions and occupational health, with a particular focus on the reduction of harmful substance usage at early stages of production.
- EU REACH regulation: covering registration, evaluation, authorization and restriction of chemicals for Manufacturers, Importers and Downstream usage.
- ISO 14040 and ISO 14044: describing the principles and framework for life cycle assessment (LCA) including goal and scope definition, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review and limitations of the LCA.
- OEKO-TEX: ensures that tested yarns and textiles do not contain illegal substances, regulated harmful substances, or known harmful and unregulated chemicals.
- Roundtable On Sustainable Biomaterials (RSB): offering feedstock certification & traceability including for more innovative materials including biobased and recycled carbon
- ZDHC MRSL - Manufacturing Restricted Substance List: includes chemicals that are banned from intentional use in facilities processing textile materials, leather, rubber, foam, adhesives and trim parts in textiles, apparel, and footwear.

FURTHER USEFUL RESOURCES:

- adidas AO1 Compliance: detailed Restricted Substance List
- Biofabricate website: Contains useful information and detailed overviews on biofabrication and material innovators
- Ellen MacArthur Foundation's 'Vision of a circular economy for fashion', 2020 - outlines the vision of a circular economy for fashion, including end of use
- European Commission website: Detailing specifications and further useful resources around biobased content and biotechnology innovation and a website dedicated to biobased material procurement.
- European Commission, 'Environmental impact assessments of innovative biobased products – Summary of methodology and conclusions', 2018 - includes LCA's of innovative biobased products
- Fashion for Good resource library
- Fashion for Good and Boston Consulting Group, 'Financing the Transformation in the Fashion Industry: Unlocking Investment to Scale Innovation', 2020
- Kering Material Standards: Standards for Innovation for materials and processes: covering key topics such as Feedstock (based on Fashion for Good Definitions), Material inputs and processing, end of use , Nanotechnology, GMO and general guidelines around impact hotspots and regulations
- Material Innovation Institute Resources:
  - Bovine leather performance standards: a summary of key attributes most brands consider with bovine leather including testing requirements and detailed performance metrics.
  - Mycelium Leather Technology Assessment: comparing leading mycelium leather innovations.
- Safer Chemistry Innovation in the Textile and Apparel Industry - evaluates the role of harmful chemicals in the production of textiles and apparel and identifies key Innovation areas while offering insights to accelerate the adoption of new safer technologies highlighting examples of numerous innovative companies.
- Supply compass: A production platform to support in identifying and working with the best suited international manufacturers. Offer useful tools for production such as tech pack creator, sampling section, international payments, and progress tracker as well as guides on e.g. Certifications & Standards
- The Mills Fabrica and Bolt Threads, 'Synbio Playbook for Techstyle Startups - A Complete Guide For Founders'
- ZDHC resource library: "Detoxing the Fashion Industry" and other useful reports

USEFUL IMPACT ASSESSMENT TOOLS:

- Ecochain environmental intelligence and impact assessment platform including free trial versions
- Ecoinvent: is one of the biggest Lifecycle Inventory Databases offering simplified LCA software tools for a basic insight on the environmental impact of a given product or service
- Kering's Environmental Profit & Loss tool (EP&L): an open source impact and business management tool providing insights into environmental impact hotspots alongside financial metrics.
- OpenLCA: an open source and free software for Sustainability and Life Cycle Assessment
- Scivera® lens: ondemand chemical management software supported by an automated approach to review chemicals and materials for toxicological hazards
- SimaPro: one of the leading LCA software solutions frequently used in academia

CONFERENCES

- Biofabricate
- Worldbio Markets Conference
- Biodesign Challenge
- Synbiobeta

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