# WHAT MAKES SILK, SILK?

## REVISITED 2023

MATERIAL INNOVATION INITIATIVE

Image Credit: Yuima Nakazato Collaboration: Spiber X Yuima Nakazato

Image Credit: Bemberg

MATERIAL INNOVATION INITIATIVE

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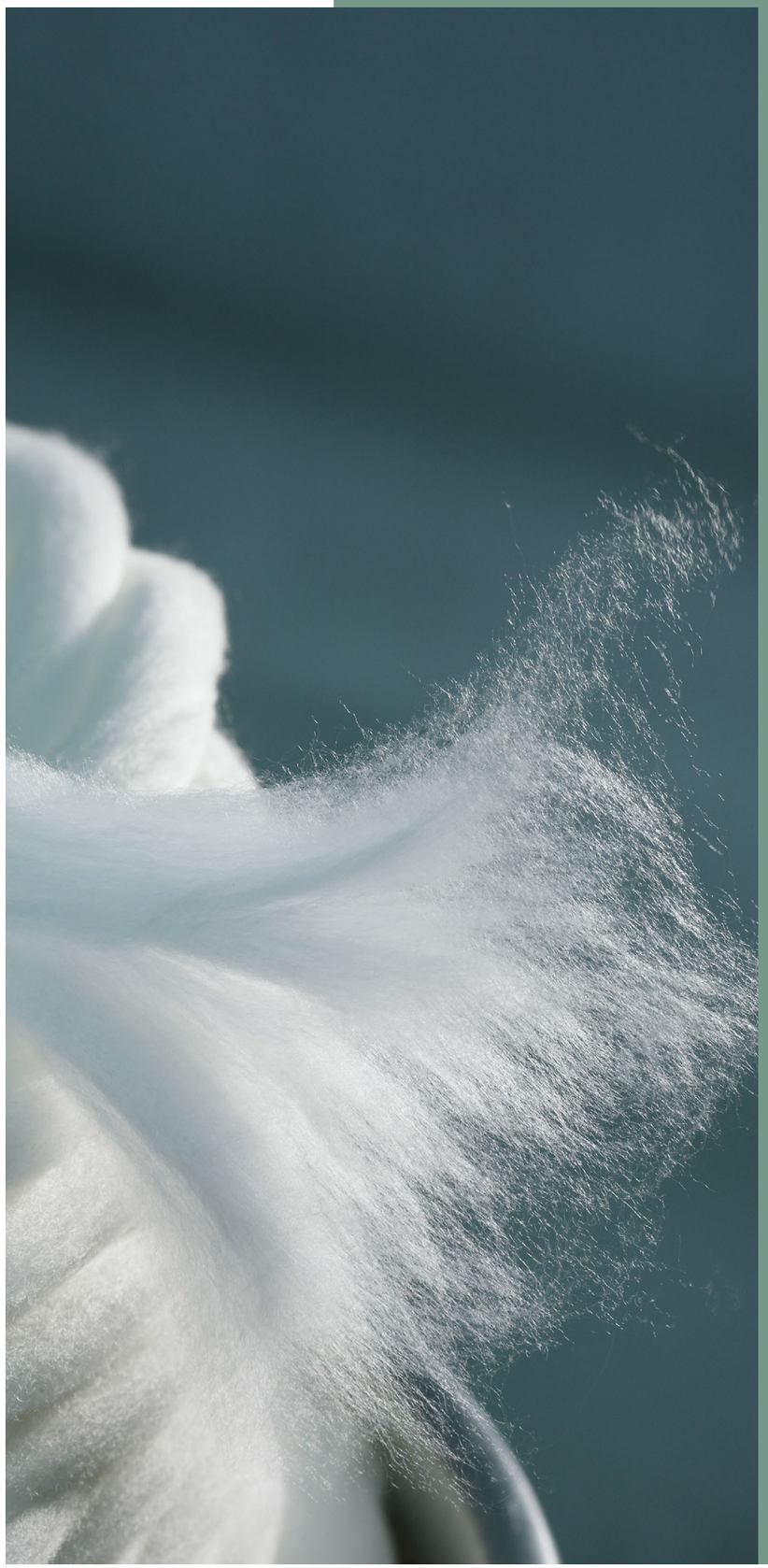

Image Credit: LENZING™ ECOVERO™ Fibers

Image Credit: Lenzing x Flavia La Rocca Photo: Flavia La Rocca

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# SILK INNOVATORS

Image Credit: LENZING™ TENCEL™

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# INTRODUCTION

Silk, the Queen of Fibers, is one of the most luxurious and ancient textile fibers, with the first silk fashion emerging in China around 2600 BCE.[1]

Recent discoveries of silk's large environmental footprint, human rights abuses, and animal welfare concerns are inspiring scientists and innovators to develop a new generation of next-gen silk fabrics that can match silk's positive attributes without harming the planet or its inhabitants.

But to dethrone the Queen, we need to answer a few questions:

- What makes silk special?
- How does silk's composition, structure, properties, and performance make it the luxurious fiber we know today?
- How can we mimic or recreate silk without using animals or petrochemicals?
- What are the greatest challenges and opportunities in creating next-gen silk?
- Do successful next-gen silk innovators already exist?

This report is an update to our 2021 **"What Makes Silk, Silk?"** report.

In this report, you will find some highlights from the original report plus notable product and scientific updates from the past two years. For anyone interested in creating or investing in a next-gen silk product, the original report is still highly relevant and contains more detail than provided in this update.

By exploring silk's unique properties and innovation opportunities, this report is intended to inspire a new generation of scientists and entrepreneurs to develop high performance, luxurious, and sustainable next-gen silk materials.


Image Credit: Ryan Duffin for Keel Labs

ALT
TEX

**ALT TEX**

**Innovation Category:** Fermentation
**Co-Founders:** Ayra Ashad and Avneet Ghotra
**Founded:** 2019
**Headquarters:** Canada

Alt Tex's patent-pending food-to-fabric technology reengineers food waste into a bioplastic fiber to create circular textiles and products. Food waste is collected from the food manufacturing industry, which would otherwise go to landfill. The company then uses fermentation technology to combine food waste with microbes to create high strength polymers.
Using melt extrusions, they are able to create filament fibers with high performance qualities like durability and versatility. Alt Tex fibers are also biodegradable and can drop-in to existing factory infrastructure: yarns can be woven or knit using existing machinery.

ALT TEX is cost competitive to other premium sustainable fabric alternatives.

Image Credit: Alt Tex

**AMSILK**

**Innovation Category:** Fermentation
**Founders:** Dr. Lin Romer and team from Technical University of Munich
**Founded:** 2008
**Headquarters:** Germany

AMSilk's Biosteel® fiber is made of spider silk protein produced by genetically engineered microbes and spun into fiber. It is a high performance filament fiber that is thinner and more delicate than traditional animal-based silk. AMSilk's material is biodegradable in marine, anaerobic, and aerobic conditions: contains no petrochemicals; is hypo allergenic; is bacteriostatic (so no odor build up); and can be dropped into the existing value chain for knitting, weaving, and dying.

AMSilk can be used in a variety of applications ranging from super fine yarn for silk-like fabric, to super resistant yarns for advanced materials such as composites or sport shoes. In medical use, their silk material is used to coat breast implants to prevent infection and reduce postoperative complications.

Image Credit: AMSilk

> *"It is possible to make silk proteins synthetically, but it is very hard to assemble the individual proteins into a fiber or other material forms. The spider has a complex spinning duct in which silk proteins are exposed to physical forces, chemical gradients, the combination of which generates the assembly of molecules that leads to silk fibers.*
>
> *Markus Buehler*
> *MIT Professor*

# WHAT IS SILK?

Silk is a fine continuous protein fiber produced by numerous insects to form cocoons or webs. Two of the most studied silks come from the larval cocoons of silkworm moths and the webs and other structures made by spiders. Silkworm silk is derived from cocoons of the larvae of the Bombyx mori (B. mori) moth and is the most common origin of commercial silk fiber and fabrics. Although silk fabric produced by spiders was never commercialized due to the difficulty in farming the cannibalistic spiders,[2] spider silk's unique engineering properties have inspired many researchers and innovators to replicate its properties for fabric applications. Silk is formed primarily from two types of protein: fibroin, which gives silk its structure and strength; and sericin, which provides a sticky, glue-like coating for silk fibers. B. mori silk fibers are generally processed to remove the majority of the sericin.

*Fig 1 The differences in structure and morphology of silkworm silk and spider silk*

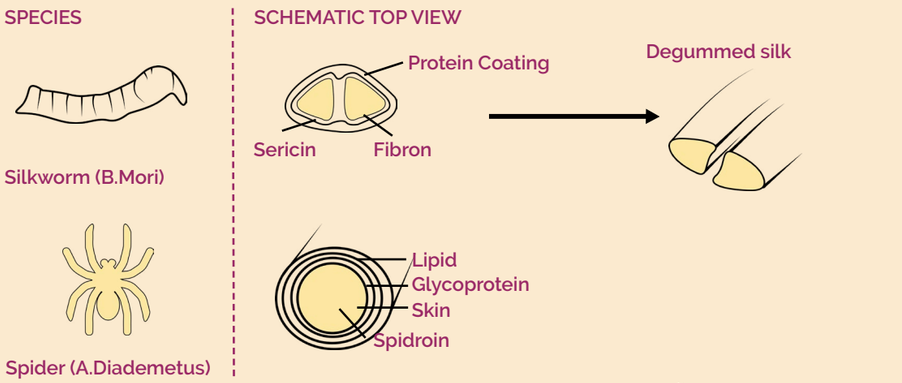
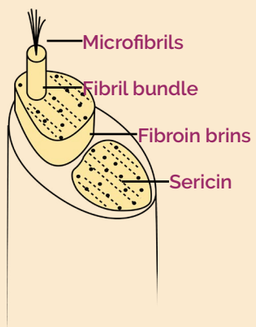



*Fig 2 The microstructure of a raw silk filament bave. (from our original, What Makes Silk, Silk? report)*




*An individual filament[3] of B. mori silk has a mass of approximately 1 denier[4] and a diameter of up to 13 microns.[5] making it much finer than a human hair.[6]*


Image Credit: Spiber Inc. Spun Yarn

Next Gen Silk Collaboration Aritzia x EastmanNaia, 2023

Image Credit: Zara x Circ; photo: Zara

**CIRC**

**Innovation Category:** Textile-to-Textile Recycling
**Co-Founders:** Peter Majeranowski and Dr. Julian Bobe
**Founded:** 2011
**Headquarters:** Virginia/USA

Circ has created a proprietary hydrothermal process to separate polyester-cotton blended textiles and recover both the polyester and cotton (cellulose) portions to be made into like-new fibers for textiles.

Not long ago, it was nearly impossible to separate and re-use fibers from cotton/poly blends - which make up the largest blend category globally - thus millions of tons of discarded clothing and textiles were destined for landfill or incineration. Circ's ability to separate and recover both portions of polyester-cotton blends is a key unlock for the industry to achieve textile-to-textile circularity.

Circ regenerates the cellulose from the cotton portion of polycotton textile waste in order to create Circ Lyocell. They are able to produce both staple and filament fibers to match virgin tree-based lyocell with the resulting fibers having the ability to look and feel like silk. Circ also regenerates the polyester into Circ Polyester that performs as well as virgin polyester. Both fibers work in existing manufacturing infrastructures, allowing for a 'drop-in' replacement to their virgin counterparts.

Circ is a B Corp certified company.

Image Credit: Eastman Naia

## EASTMAN NAIA

**Innovation Category:** **Cellulosics**
**Founded:** **1920**
**Headquarters:** **Tennessee/USA**

Eastman Naia uses cellulosic fibers to make filament yarn and staple fibers into sustainable textiles. They use sustainably sourced wood pulp and environmentally sound chemicals with low impact manufacturing processes. Their materials are biodegradable, compostable and compatible with molecular recycling.

Eastman holds FSC and PEFC Chain of Custody certifications and their material is produced in a closed-loop process where solvents are recycled back into the system for reuse. It is OEKO-TEX Standard 100 and is certified as having no hazardous chemicals by ZDHC. They use a third party reviewed LCA and received the TUV AUSTRIA OK biodegradable certification for freshwater and soil environments and the 'OK compost' certification for industrial settings.

Performance features are: home laundering, no shrinkage, shape memory, reduces odor, easy stain removal, no pilling, hypoallergenic.

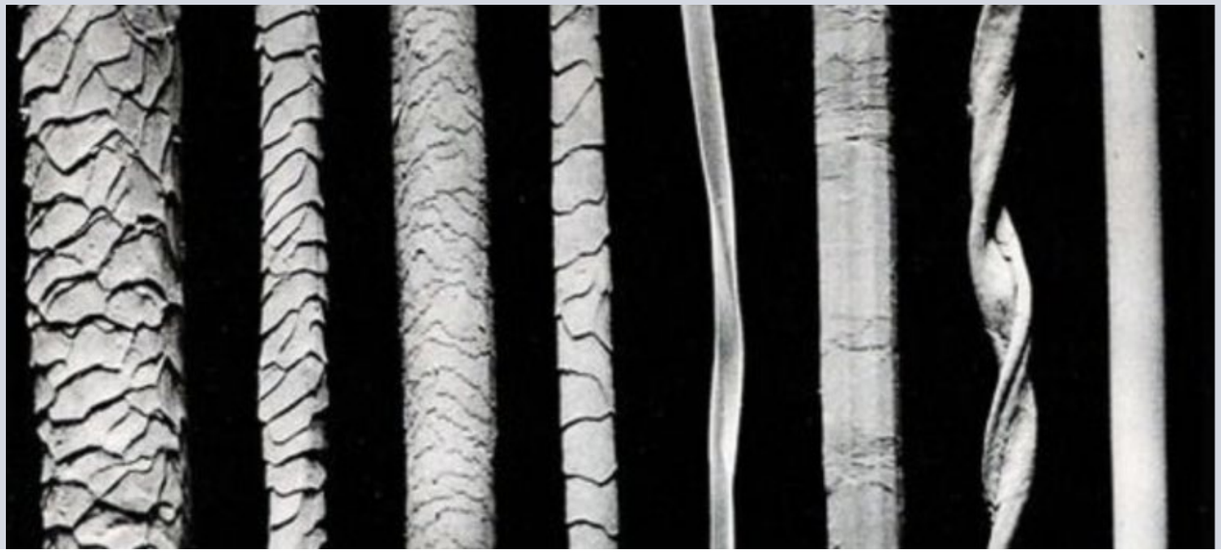
With a smooth silky-soft handfeel and drape, it can be made in lustrous or matte finishes and takes color easily. Naia is available in knits and wovens. Naia also offers Naia Renew which is 60% cellulosic and 40% certified recycled waste materials.

# WHAT MAKES SILK SPECIAL?

Silk fiber is unique. At up to 800 meters (~2,625 feet) long, the bivoltine[7] B. mori silk is the longest continuous filament fiber in nature.

> **Scroop is so integral to the silk experience that Japanese textile manufacturers use sound-wave tests on new fibers of imitation silk in an effort to match the susurrus of the real thing.[8]**
>
> **J.E. Boyce**
> **MIT**

*Fig 3 A diamond in the rough – silk is the only natural fiber that forms a smooth, continuous filament.[9]*



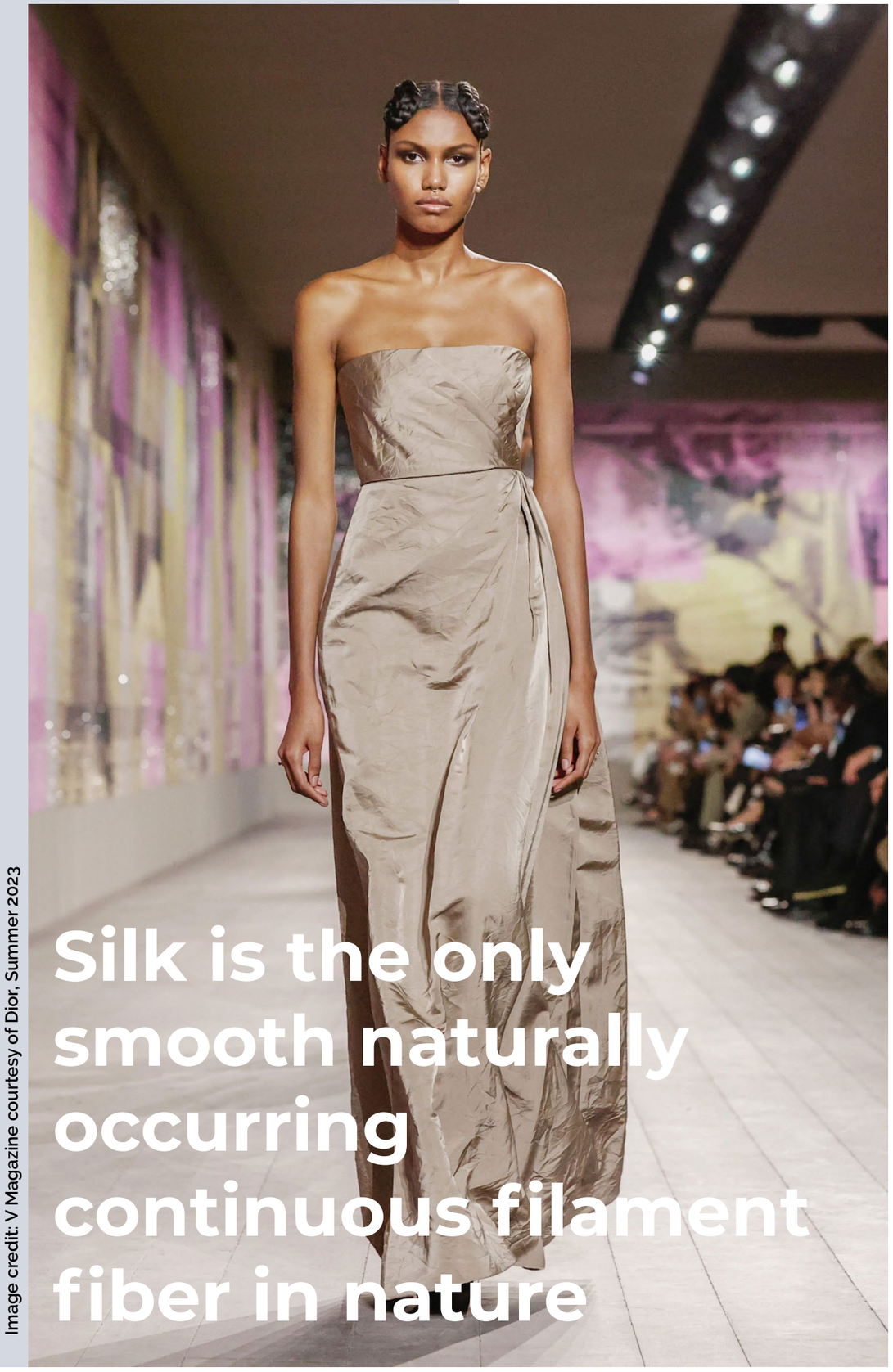
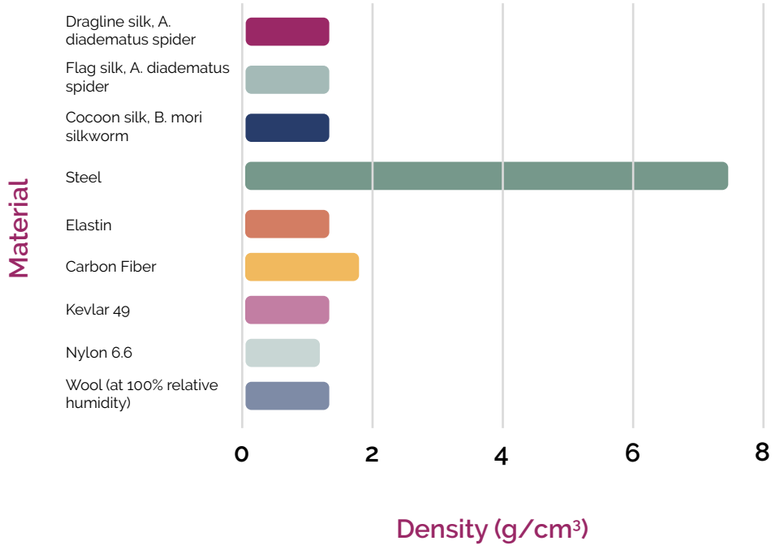



Image credit: V Magazine courtesy of Dior, Summer 2023

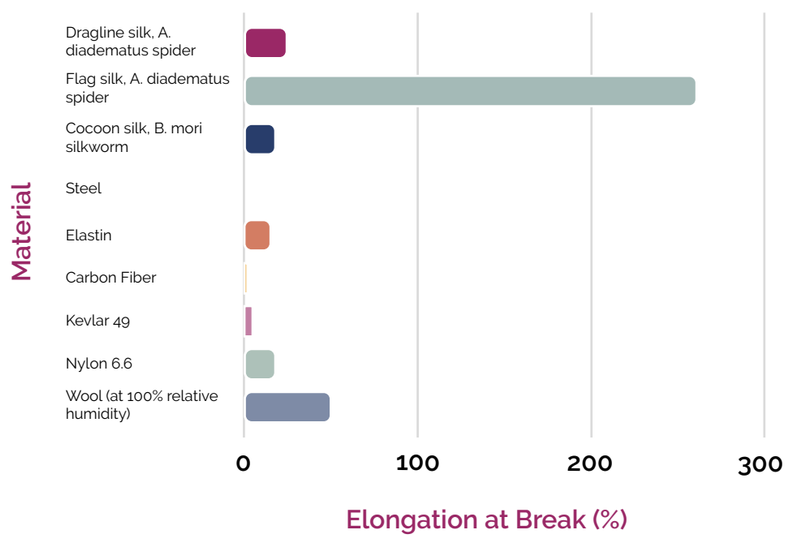
**Silk is the only smooth naturally occurring continuous filament fiber in nature**

As shown in the graphs below,[10] silk has a unique combination of density,[11] elongation at break,[12] tensile strength,[13] stiffness (modulus),[14] and toughness,[15] Spider silk has by far the highest toughness of the compared materials (including being three times tougher than Kevlar) and has a remarkable ability to stretch without breaking. Silkworm silk is also tougher and more stretchable than most materials.

## DENSITY




## ELONGATION AT BREAK

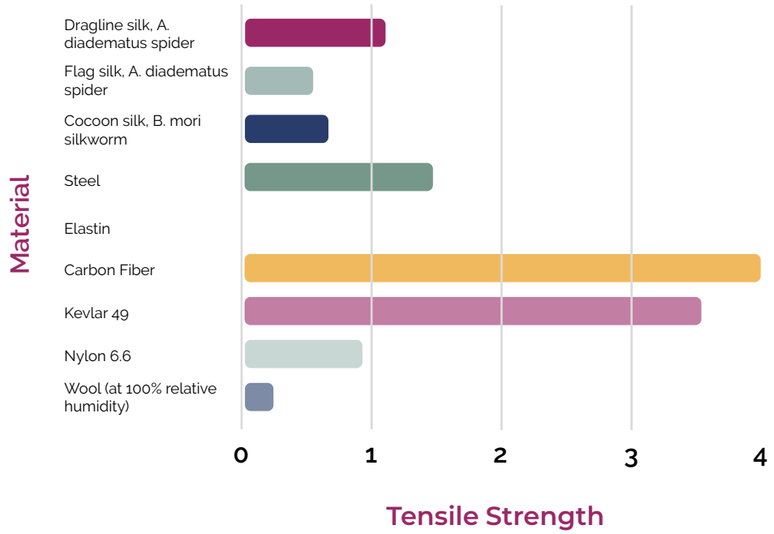



Next Gen Silk Collaboration
Reformation x Eastman Naia, 2023; photo: Reformation

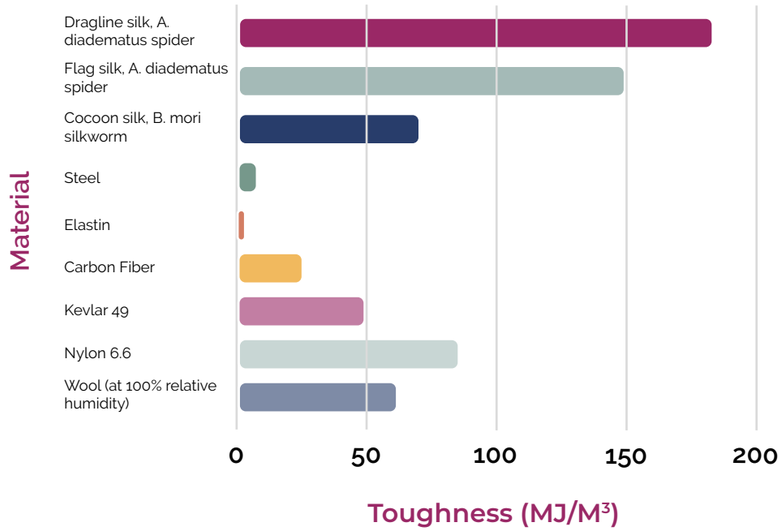
Image Credit: Keel Labs Process

Image Credit: LENZING™ ECOVERO™ Fibers

## TENSILE STRENGTH




## TOUGHNESS




Next Gen Silk Collaboration
Monique Lhuillier w/Tencel

## WHAT MAKES SILK SO SPECIAL?

- Silk's smooth, continuous filament gives silk yarn some of its unique properties such as strength, elasticity, and resistance to pilling.
- In contrast, all other natural fibers[16] are staple fibers of discrete lengths and are bound by aggregation or entanglement. These fibers may easily shed or pill under the sheer forces of abrasion.
- The trilobal shape of silk fiber, its translucency, and its smooth surface contribute to its high luster or "shine".[17]
- Silk absorbs natural, nontoxic dyes easily, imparting vivid colors to its fabrics.
- Unlike animal silk, synthetic silk alternatives such as nylon and polyester often require disperse dyes, some of which are toxic and carcinogenic.[18]
- Silk's protein-based composition makes it adaptable to different environments and thus an all-weather fabric.
- Silk's combination of low thermal conductivity and capacity to absorb perspiration is what makes silk fiber comfortable in nearly all weather conditions.
- Silk textiles come in a variety of weights, hands,[19] sheen, drape, and sound.

If residual sericin protein is left on as a coating, silk has a drier hand feel with a frictional sound when the fabric is rubbed together.

Taffeta silk has a crisp sound when rubbed together and makes a "swishing" or "scroop" sound when the wearer walks. This sound is sometimes used as a validator for the quality of silk.

The smoother 'silent' silk has less sericin. When wearing this type of lightweight silk, one might witness a "glissade," which describes the fabric movement.

# ettitude

**ETTITUDE**

**Innovation Category:** Cellulosics
**Founder:** Phoebe Yu
**Founded:** 2014
**Headquarters:** California/USA

Originally a B2C home goods company, in 2023, ettitude added a B2B arm for their woven Clean Bamboo textile. Clean Bamboo woven material has high thread counts with a refined silken hand and surface sheen. ettitude's Clean Bamboo fiber offers performance properties like: thermal temperature regulating, hypoallergenic and anti-fungal. It is also biostatic and deodorizing.

Bamboo is a regenerative grass that grows quickly after harvesting. Clean Bamboo is made with food grade, non-toxic chemicals and uses a closed-loop water system in which 98% of the water and solvents from production are recycled.

ettitude produces globally, including manufacturing sites in South America, Europe, and South East Asia.

ettitude has ECO and 100% FSC certifications, uses OEKO dyes, requires traceability from farm to finished product, and are Canopy Hot Button approved.

ettitude became a certified B Corp in 2022.

Image Credit: ettitude

Image Credit: Kintra fabrics in various constructions at their Brooklyn, NY lab_Kintra

# KINTRA

**KINTRA**

**Innovation Category:** Biosynthetics
**Co-Founders:** Billy McCall and Alissa Baier-Lentz
**Founded:** 2018
**Headquarters:** NYC/USA

Kintra Fibers has developed a new and proprietary bio-synthetic material that is:

- 100% bio-based (from glucose via fermentation) inputs
- Biodegradable
- Compatible with standard polyester production equipment

The team can fine-tune their resin and yarn, resulting in yarns applicable to a wide range of knit and woven textiles. Some of the fabrics they've made to date are suitable for applications traditionally made with animal-based fibers, such as a satin woven with a silk-like hand feel, and a knit with a cashmere-like hand feel. Additionally, Kintra's brand and mill pilot partners are using Kintra yarns as an alternative to traditional synthetics such as PET polyester and Nylon.

# HOW CAN SILK BE IMPROVED?

Silk has many positive attributes, but also several drawbacks:

- Many woven silks are delicate, requiring dry cleaning, hand washing, and steaming.
- Silk may shrink when machine-washed. Spider silks are especially apt to shrink substantially after exposure to water.[20]
- Silk fabrics have low long-term heat resistance and degrade when ironed.
- Silk fabrics may bleed and stain easily.
- Silk has poor resistance to UV light. Exposure to UV sunlight can result in fading of the dyes or yellowing of white silk and can degrade the mechanical properties of silk fiber.
- Despite the high strength of silk, the fine nature of silk filaments and their use in thin fabrics, particularly knitted silk, can make them susceptible to damage like snags.
- Silk fabrics attract static, which is uncomfortable for the wearer.
- Silk has a relatively high cost compared with cotton or synthetics and is therefore often reserved for luxury apparel and accessories.
- Because it is a natural fiber, there can be fiber inconsistencies or “slubs”.

Incumbent Silk: Performance Target:
Valentino, Fall 2022 collection, photo credit: Nadine Ijewere. Silk chiffon cape and silk crepe couture trousers. You can immediately see the weight difference and opacity of chiffon vs this trouser weight crepe.

# KEY TARGETS FOR CREATING SILK ALTERNATIVES

With advancements in material and fiber science, we can create affordable, high performing, and more sustainable fibers that mimic the positive properties of silk and improve upon its negative attributes.

The following are attributes of silkworm silk broken down by fiber and fabric.

## Fiber Properties:

- Continuous filament
- Smooth translucent fibers for luster
- Fine (low denier, small diameter) fibers
- Hierarchical structure, crystallinity, and alignment to impart strength and toughness (see pp. 12-15 of MII's full silk report for more information.)
- Low density
- Able to take non-toxic dyes
- Suitable for use in existing knitting, weaving equipment, and infrastructure
- Versatile fibers that can be woven to create classic silk textiles

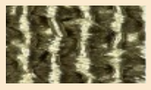
By combining different arrangements of filaments into types and sizes of yarns and weaving those yarns into varying patterns and densities, a variety of silk fabric types are possible with unique aesthetics and performance.

*Optical microscopy of various silk fabric swatches, taken at 200x magnification. Scale bar is 200 microns.*

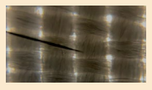

Silk Shantung


Silk Double Georgette

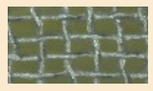

Silk Habotai or China Silk


Silk 4-ply Crepe


Silk Crepe de Chine


Microscopic view of Taffeta

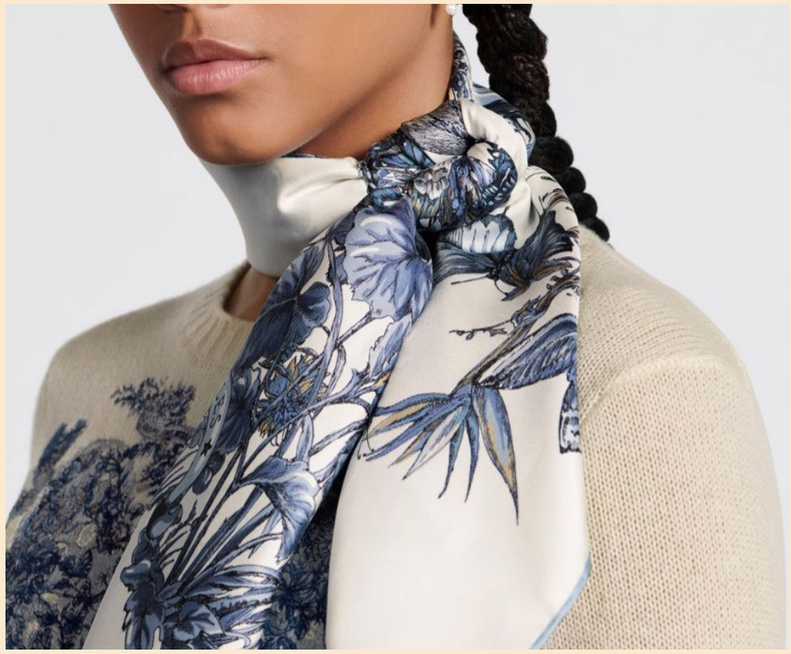

Silk Charmeuse


Silk Chiffon


Silk Mesh Tulle


Silk Plain Organza

Image Credit: LENZING™ TENCEL™ Fibers



**Incumbent Silk: Performance Target:**
**Dior, FW 2023, Photo: Dior**
**Silk twill scarf – the silk fibers and twill weave are super fine, enabling a tiny hand-rolled hem on all four sides. Because the twill is so fine, it has drape and minimal 'roundness' which makes knotting cleaner and less bouncy.**

## Fabric Properties

- Soft handfeel
- Luster/lustrous surface
- Different weave capabilities (diverse weaving imparts a different hand and drape, e.g., taffeta hangs and tailors very differently from a sateen)
- “Scroop” - the signature silk sound and movement in taffeta
- “Glissade” - the signature dreamlike movement when someone is wearing lightweight silk such as chiffon
- “Flutter” of silk satin
- Comfort - absorbent in warm weather, insulation in cold weather; due to triangular fiber, does not sit against skin
- Diverse weights
- Resistant to pilling and abrasion
- Able to take color brilliantly
- Flame retardant

## Improvement Potentials

- Decrease environmental footprint
- Increase UV resistance
- Decrease tendency for static build up
- Increase mechanical properties for high-performance applications, i.e., stretch
- Decrease shrinkage
- Increase launderability
- Decrease cost
- Increase stain resistance
- Increase durability
- Fiber consistency
- Harm no animals!

A true silk mimic needs to retain the luxurious properties – especially the look and feel – of natural silk in order to be successful.

**“New fibres came as a result of trying to create a replacement for silk. Now we have the possibility of a replacement that really is silk.**

**John O’Brien, DuPont Central Research**

Incumbent Silk: Performance Target:
Valentino Couture Spring 2023; photo: Vogue
If this picture had sound, you would hear the “scroop” when the model walks wearing this voluminous taffeta gown.

Lenzing's Tencel Lyocell fibers and Tencel Luxe filament yarn were featured on the red carpet at the Oscars. The fashions that Tati Gabrielle (above) wore are fully biodegradable and compostable. Photo: Angela Weiss

Lenzing

Innovative by nature

**LENZING**

**Innovation Category:** Cellulosics
**Founder:** Emil Hamburger
**Founded:** 1892 as a pulp and paper mill; added fiber and raw material in 1940s
**Headquarters:** Lenzing, Austria

Lenzing products use sustainably sourced and harvested trees to make wood pulp and cellulosic fibers. They recycle and reuse their water and excess water is cleaned before returning to nature. Fibers are certified by Canopy, the EU Ecolabel, FSC, and PEFC. Lenzing fibers are biodegradable in industrial, home, soil, freshwater and marine conditions.

Lenzing has a wide range of cellulosic products – Tencel™ is their flagship brand for textiles. It is smooth, soft, lustrous and has drape. Within the Tencel™ family are: Lyocell, Modal, and Lyocell Filament. Their silk-like viscose product EcoVero ™ has a much lower environmental impact than generic viscose. It is biodegradable, sourced from sustainably harvested wood pulp, uses up to 50% less water and emits up to 50% fewer carbon emissions than generic viscose, and relies on a transparent supply chain. A unique attribute of EcoVero ™ is its ability to come in black.

The Lyocell Filament is an extremely fine yarn and offers a liquid-like drape and vibrant color.

In Lenzing's own words, they produce a new botanical alternative to silk, with the properties that make silk so valuable.

Image Credit: Nanollose's "100% Nullarbor20" Single Jersey

nanollose

**NANOLLOSE**

**Innovation Category:** Cellulosics
**Co-Founder:** Dr. Wayne Best
**Founded:** 2011
**Headquarters:** Australia

Nanollose's flagship product "Nullarbor" is the result of a scientific goal of creating a cellulosic material without trees, arable land, or the associated use of irrigation, pesticides, and other resource-intensive inputs. Their fermentation process is very similar to the process of converting wine to vinegar. They are able to use a variety of waste but currently, their cellulose is made mainly from waste coconut water from the food and beverage industry.

The material is available in several iterations including a silky single jersey and a fine woven. In February 2022 they conducted their first pilot spin with Birla and made 260kg of Nullarbor-20 which was converted to a variety of fabrics by their partners. They now have pilot production facilities in India and have produced half a ton of fiber which has been converted into yarns, fabrics, and garments.

Nullarbor fiber and fabrics behave like conventional lyocell with the exception that they are significantly stronger than conventional lyocell made from trees. Like conventional lyocell, it can be hand or machine washed.

# WHY NEXT-GEN SILK?

## The Problem: The Silk Industry Harms People, Animals, and the Planet

The silk industry accelerates climate change and environmental degradation, relies on inhumane and unsustainable animal agricultural practices, and offers few protections for workers in processing plants.

### Silk Production and Processing Harms the Environment and Accelerates Climate Change

Silk is considered to be one of the most environmentally damaging fibers. Environmental impact assessments of silk production, while limited,[21] indicate that mulberry farming and silk processing are energy- and water-intensive, have a high Global Warming Potential, and contribute to eutrophication. A life cycle assessment (LCA) conducted on raw silk produced in India revealed that silk has the highest environmental footprint across nearly all reported categories compared to cotton, nylon, or wool.[22]

White space opportunity for more research: The silk industry currently relies upon one silk LCA conducted in India despite China being the largest silk market. The silk industry repeatedly cites this issue in response to environmental comparisons, yet the industry also fails to produce additional LCAs.

Petrochemical-derived synthetic silk alternatives such as nylon 66[26] (featured in the table opposite) are nonrenewable and nonbiodegradable. Synthetic silk alternatives also shed microplastics and other toxins that poison ecosystems, harm the planet and its inhabitants, and fuel climate change.

Next Gen Silk Collaboration
A.ROGE HOVE x Renewcell, 2023

Image Credit: Mara Hoffman x Circ

*Table 1. Environmental impact of silk production compared with other fibers[23].*

| | Raw Silk (India) | Cotton (China) | Nylon 66 | Sheep Wool (US) |
|---|---|---|---|---|
| Global warming potential (100 years; kg CO2eq/ kg) | 51.5 | 3.4 | 8 | 18.5 |
| Cumulative energy demand (renewable; MJ/ kg) | 1349.9 | 19.7 | 1.3 | 81.7 |
| Cumulative energy demand (nonrenewable; MJ/kg) | 110.1 | 0.1 | 0.0007 | 0.1 |
| Ecotoxicity (CTUe/kg) | 522.8 | 71.2 | 0.0006 | 3.4 |
| Agricultural land occupation (m2a/kg) | 19.7 | 7.8 | 0.0002 | 53.5 |
| Blue water footprint[24] (m3/kg) | 24.6 | 7 | 0.2 | 0.2 |
| Freshwater eutrophication[25] (g Peq/kg) | 4.8 | 0.8 | 0.3 | 0.5 |

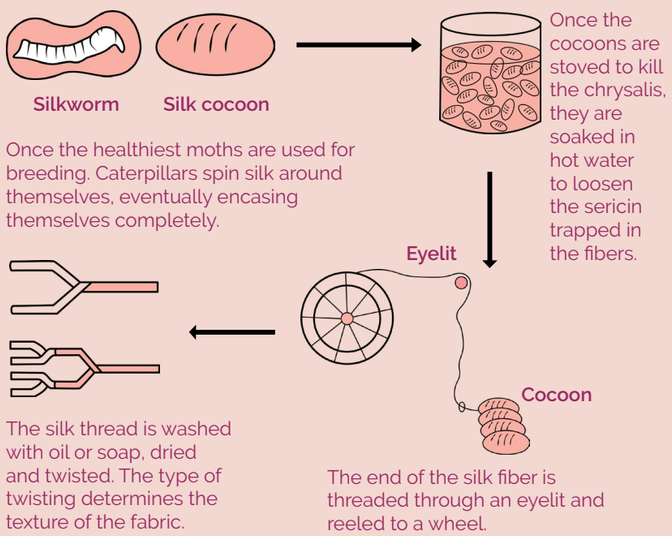
## Silk Processing Plants Often Offer Low Wages and Poor Working Conditions

The silk industry's supply chains lack transparency and accountability. Employees in many silk processing plants work long hours with little pay. Both child labor and bonded labor[27] are used in some silk processing plants, particularly in India, where they have minimal health and safety protections.[28]

## Up to 1 Trillion Silkworms Are Killed Annually to Produce Silk[29]

The most common method for extracting silk involves boiling animals alive in their cocoons. An alternate method of producing silk that is promoted as humane is the "Ahimsa" method. According to a Beauty Without Cruelty investigation, while animals aren't directly killed to produce silk using this method, moths are crushed to death in mixers, discarded after mating, and "either way [the traditional or Ahimsa production method] at least 1500 lives are lost for just 100 grams of silk."[30] Although research on insect sentience and nociception is still evolving, there's no need to enact harm on such a massive scale when we can create more humane, sustainable alternatives.

*Fig 4 A simplified overview of silk processing*





Next Gen Silk Collaboration
Mara Hoffman x Circ, photo: Mara Hoffman


Image credit: Mara Hoffman x Circ

Image Credit: Mara Hoffman x CirC

Image Credit: Mara Hoffman x Circ

Image Credit: Mara Hoffman x Circ

ORANGE FIBER

**ORANGE FIBER**

**Innovation Category:** Cellulosics
**Co-Founders:** Enrica Arena
**Founded:** 2014
**Headquarters**: Italy

Orange Fiber was amongst the first to offer a next gen silk alternative. They make Circular fabrics from citrus fruit waste in Italy with production sites in Sicily.

With the company's patented method, cellulose is extracted from citrus waste and chemically processed into polymers that are spun into fibers. These acetylated cellulose fibers can be blended with other sustainable fibers.

Fabrics can be customized to be matte or shiny and can be dyed, colored, or printed.

In 2021, they formed a partnership with the Lenzing Group allowing them to turn their citrus pulp into the first TENCEL ™ branded Lyocell fiber.

Image Credit: Luca Distefano Photographer x Orange Fiber

Image Credit: Renewcell x H+M

# RENEWCELL

**RENEWCELL**

**Innovation Category:** Recycling
**Co-Founders:** Dr. Christopher Lindgren, Prof. Gunnar Henriksson, and Prof. Mikael Lindström
**Founded:** 2012
**Headquarters:** Sweden

Renewcell uses recycling technology to break down used cotton and other cellulose-rich textiles and transform them into a new biodegradable raw material, Circulose® pulp, which can be used to make biodegradable virgin quality viscose, lyocell, modal, acetate, and other kinds of biodegradable regenerated fibers (also called man-made cellulosic fibers). These fibers are then spun into yarns, wovens, or knitted into fabrics.

Image Credit: Alexander Donka for Renewcell, shredded textile waste

## Synthetic Alternatives to Animal Silk

Popular synthetic alternatives to silk include polyester and nylon.

These synthetic materials contain chemically stable microplastics (<5 mm), which accumulate and persist in ecosystems for hundreds of years, as well as toxins that poison ecosystems, harm animals, and fuel climate change.

Microplastics shed by synthetic silk alternatives are pervasive and circulate throughout all of Earth's systems.

Microplastics are proliferated around the globe by air, rain, lakes, rivers, and oceans, and are found in nearly every aquatic environment tested for their presence, including in deep sea trenches, remote lakes, and Antarctica.

The International Union for Conservation of Nature and Natural Resources (IUCN) and Global Microplastics Initiative determined in separate studies[32 33] that microfibers from synthetic textiles (as opposed to other sources) are the number one source of microplastics in oceans.

Image Credit: Unsplash

**In 2017, the United Nations estimated that as many as 51 trillion (500 times as many stars estimated to be in our galaxy) particles of microplastic are in the world's seas and oceans alone.[31]**

Image Credit: Unsplash

## Microplastics Harm Ecosystems and Animals in Myriad Ways

Microplastics shed by synthetic silk alternatives damage ecosystems and harm trillions of animals by reducing their food intake, delaying their growth, altering their behaviors, decreasing their reproductive capabilities, causing inflammation and oxidative damage, poisoning them with toxins, and leading to premature death. Microplastics cause the most damage to ecosystems through harming keystone species—including species of zooplankton, crabs, and coral—all of whom serve critical functions for supporting entire ecosystems.[34]

Without intervention, the use of synthetics or animal-derived silk will continue to grow.

As research continues to surface about synthetic silk materials' environmental and animal welfare impacts, brands and retailers are under pressure to reduce their reliance on these materials. In fashion especially, there is an increased push to equate synthetic materials with "plastics," necessitating a move back to "natural" animal-derived materials. Unfortunately, without providing more sustainable, humane alternatives, this backlash against synthetics will likely lead to a resurgence in animal-derived silk, which also harms the planet and its inhabitants.

## Next-gen Materials Are the Solution

The only truly effective long-term solution to the harms caused by silk and its synthetic alternatives is to replace them with next-gen materials that replicate their positive aesthetic and performance properties while eliminating their negative externalities. Next-gen silk materials are environmentally preferable and animal-free alternatives to animal-derived silk and its petroleum-derived synthetic counterparts.

**For more information, please read MII's Impacts of Synthetic Materials on Animals report.**

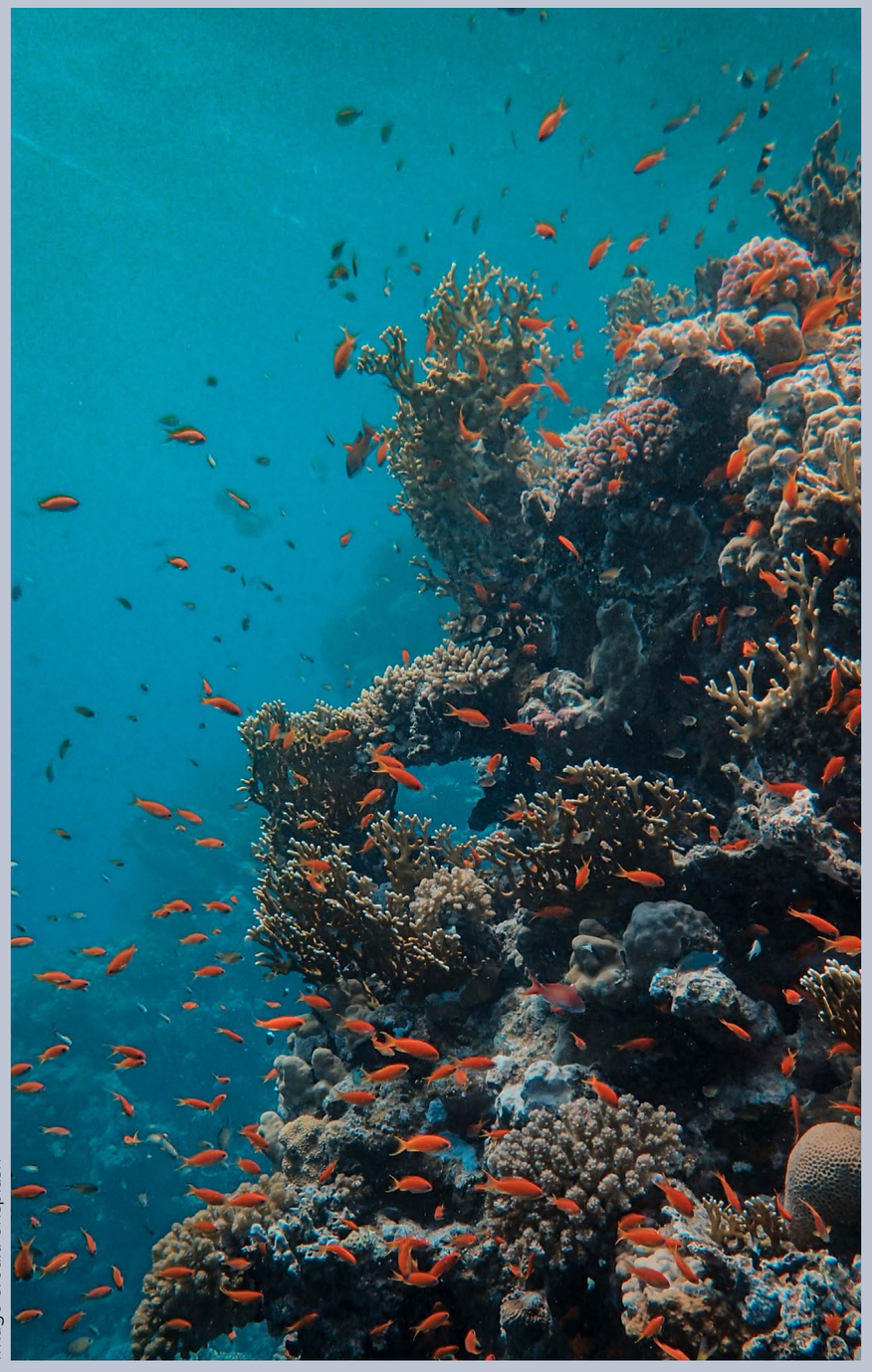
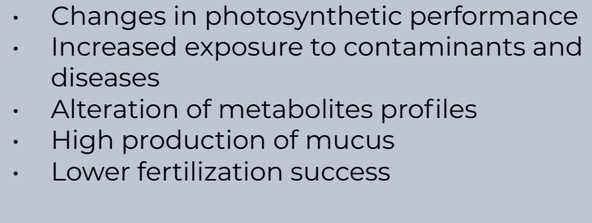


Image Credit: Unsplash

## Microplastics in Corals, an Emergent Threat

### Selectivity of stress-tolerant species



### Effects in Corals:

- Reduced growth
- Increased mortality among Symbiodiniaceae, the unique algae that live inside corals and supply them with vital nutrients
- Impairment of reproduction
- Coral bleaching
- Increase in diseases
- Increase in the activities of antioxidant enzymes
- Tissue inflammation
- Decrease of detoxifying and immune enzymes
- Decreased calcification
- Impairment of feeding performance
- Decrease in food intake
- Necrosis
- Reduction of fitness
- Changes in photosynthetic performance
- Increased exposure to contaminants and diseases
- Alteration of metabolites profiles
- High production of mucus
- Lower fertilization success

# Once microplastics enter marine ecosystems, they can persist for centuries and are nearly impossible to remove

# THE OPPORTUNITY: ENVIRONMENTALLY PREFERABLE AND HUMANE NEXT-GEN SILK

In today's era of unparalleled materials and manufacturing innovation, we now have the ability to match the performance and aesthetics of silk without relying on animal agriculture or petrochemicals. Novel suites of sustainable synthetic polymers, natural proteins, and hybrid materials can act not only as replacements for silk, but potentially replace polyester and rayon as well.[35]

Incumbent Silk: Performance Target : Ralph Lauren SS 2024 Photo: Angela Weiss for Harper's Bazaar. Silk lamé is as fluid as it gets.  Styled in this one shoulder gown it is like liquid gold.

## Here are just a few of the reasons why innovation in silk is a great opportunity:

**Small volume, big impact.** The smaller global production of silk can help early next-gen innovators produce comparatively large amounts of silk fabrics. To produce 5% of the annual global production of silk, one would only need to produce 8,500 tons of silk. To do the same for polyester, one would need to produce 3,050,000 tons of polyester. Even early production runs by a silk-replacement start-up can make a huge impact on market volume.[36]

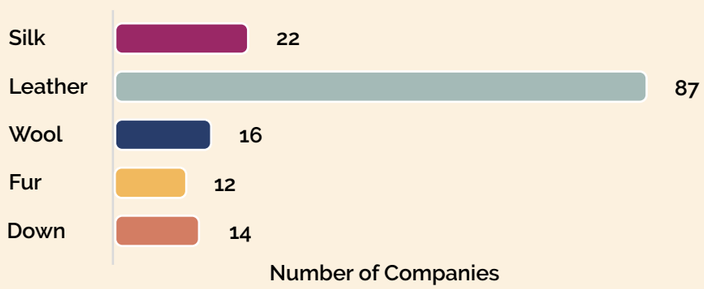
**Luxury is high value.** Silk is a luxury material with a much greater profit margin than its synthetic alternatives. Raw silk (3A grade) costs >$50/kg, while polyester filament yarn costs ~$1/kg.[37]  The higher profit could enable technology with relatively high production costs such as precision fermentation to attain price parity. The current silk market is projected at ~$17 billion.[38]

**Novel material, new markets.** Recombinant silks,[39] such as those from spiders or other species, are currently an untapped market for textiles, as they cannot be harvested naturally. These next-gen replacements for silk are some of the strongest and toughest textile fibers in existence. They have the potential to enter new markets such as military textiles, sports apparel, outdoor wear, and technical textile applications.

**Less competition.** While successful next-gen silk innovators are beginning to emerge, the next-gen silk space is not crowded. In contrast, competing with the global chemical powerhouses that manufacture petroleum-based polyester silk alternatives could be a daunting undertaking.

**A stepping stone to synthetics.** A novel, high performing next-gen silk replacement will also replace silk's petroleum-derived synthetic alternatives. In order to meet their environmental, social, and corporate governance (ESG) goals, brands are increasingly searching for nontoxic replacements to petroleum-based synthetic materials that rely on renewable, abundant, and regenerative resources.

### INNOVATORS BY CATEGORY



# SILK INNOVATION FUN FACTS

## Next-gen silk can come from unlikely places – from spiders to squid, bacteria to bamboo

Scientists have been working for decades to unlock the genetic power and wonder found in tiny arachnids and ocean mollusks. These special proteins have incredible versatility and strength that can lead to a wide range of end uses, including silk filament fiber.

Who knew? It turns out that plants are great hosts for growing silk proteins. This process begins by encoding silk genes in plants. After the plants grow, they are harvested and processed to isolate the silk proteins. These proteins can then be transformed into a silk filament fiber.

Regenerative bamboo is another plant that has proven its versatility and definitely earned its keep! When treated with nontoxic chemicals, this versatile fiber is soft, makes superfine yarns, colors easily, and has natural performance properties.

Updated recycling processes can yield silk-like filament fibers, saving discarded apparel and textiles from landfills and incinerators.

### Recycling has come a long way and just in time to aid the textile industry and the planet!

Scientists have figured out how to capture $CO_2$ (yes, even the $CO_2$ coming from textile plants) and treat it with special enzymes to convert $CO_2$ into filament cellulosic lyocell.

Fermentation is not just for vinegar and kombucha. Microorganisms are coded with proteins. They are fed nutrients like sugars or starches to grow. The fermentation happens inside of a bioreactor. After fermentation, the protein is extracted, dried into pellets, melted down and spun into filament fiber.

Image Credit: AMSilk

Image Credit: Freepik

Incumbent Silk: Performance Target:
Brunello Cucinelli Spring 2021, ready-to-wear; photo courtesy: Brunello Cucinelli
The photo might be a few years old but the beauty and dreamlike vision of silk chiffon is timeless. It floats and one can witness “glissade” when in motion.

Image Credit: Rubi Laboratories

# RUBI

**RUBI LABORATORIES**

**Innovation Category:** Cellulosics
**Co-Founders:** Neeka and Leila Mashou
**Founded:** 2021
**Headquarters:** California/USA

Growing up in California, the Mashou sisters were steeped in fashion due to their family-owned fashion brand Bebe. Not wanting to give up on fashion despite its environmental impact they combined their sci-tech training to create a solution to fashion's unsustainable problems. Trees were the inspiration and the guiding principle behind their work. By engineering a unit to capture the $CO_2$ coming out of factory flues, they use a cell-free enzymatic process to convert the $CO_2$ into pure cellulosic pulp. There is zero $CO_2$ waste in the process. The cellulosic pulp is then spun into fibers via wetspinning. They are able to create a lyocell yarn suitable for apparel. The fiber is silky and can be used in a lot of similar applications to animal-based silk and polyester.

The fiber plugs into existing manufacturing equipment and has price parity with lyocell.

# CHALLENGES

To successfully create next-gen silk, innovators must understand the current landscape and strategies for next-gen silk development, the challenges associated with next-gen silk innovation, and the unique next-gen silk white spaces and market opportunities.

## Big Picture Challenges

Like all startups in the next-gen materials space, the targets that next-gen silk innovators must meet include:

- **Performance** - having desirable attributes for functionality
- **Aesthetics** - must be compelling and inspiring
- **Accessibility** - providing a drop-in solution that works for textile manufacturers and brands
- **Sustainability** - contributing to lower environmental impacts compared with animal-derived silk and its synthetic replacements
- **Price** - attaining price parity with silk
- **Scale** - achieving high production volumes at reasonable prices

## Fermentation Approaches

One of the most exciting new technologies for production of next-gen silk is fermentation. Next-gen materials are categorized by their main inputs, which can be plants,[40] microbes,[41] mycelium,[42] cultivated animal cells,[43] recycled materials, and more.[44] Microbe-derived silk, which is one of the most common types of next-gen silk, is typically created using a process called precision fermentation.

Image Credit: storage.mlcdn.com

Louis Vuitton, Spring 2024 Ready-to-Wear; photo: Filippo Fior, Gorunway.com
Heavyweight silk satin enables this jacket to have a full, rounded and voluminous shape that stands away from the body. A light weight silk satin would not be able to take and hold the sharp crease that we see in the skirt.

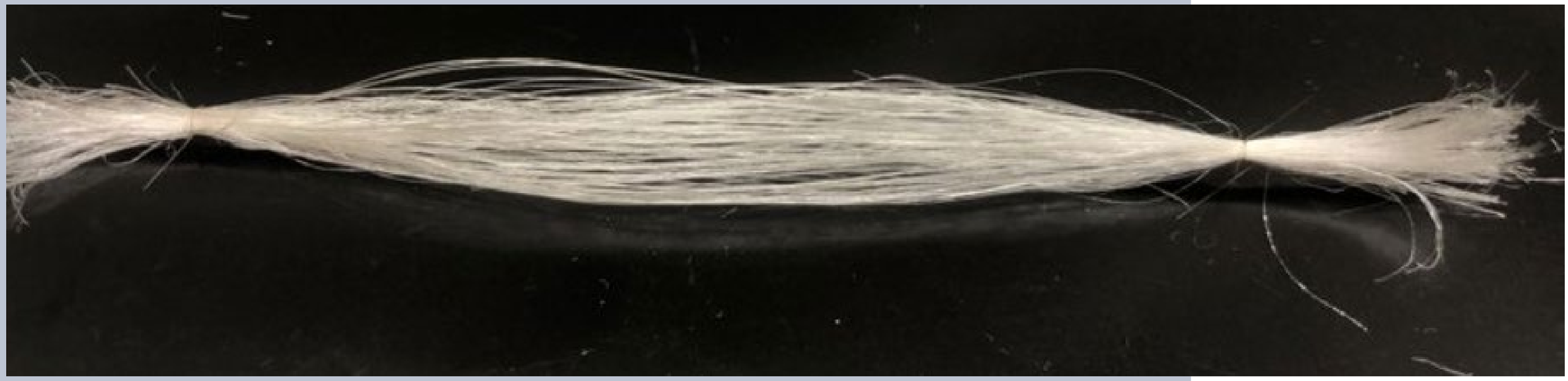


*Fig. 5. A bundle of recombinant spider silk protein fiber produced by Dr. Rising's research lab.* [49]

Traditionally, fermentation is used in the production of alcoholic beverages and fermented foods. With the help of recent advances in gene editing, fermentation is now capable of producing proteins and other biopolymers that can be transformed into next-gen materials. This advanced fermentation technique is referred to as precision fermentation.

To create silk using this process, DNA strands that contain instructions on how to produce silkworm or spider silk proteins are inserted into host microbes such as yeast or bacteria. The host microbes are then placed under optimal growing conditions in a bioreactor and fed nutrients (feedstocks) that enable them to replicate these proteins. Once a sufficient quantity of recombinant silk proteins are made, they need to be removed from the bioreactor, separated from their host, and purified before they can be transformed into silk fabrics.[45]

One of the biggest challenges currently facing this technology is yield. Getting bioreactors to churn out high volumes of silk protein has impeded the success of this approach.

Recently, Professor Anna Rising's lab at the Karolinska Institutet was able to achieve >15 g/L yield of spider silk protein in a lab-scale bioreactor, a 10-fold increase in yield compared to previous studies. (This may also be the highest protein expression level, regardless of protein type, ever reported!)[46]

Other researchers have conducted a technoeconomic analysis of spider silk production, and identified that a goal of 10 g/L yield would result in a $23/kg product.[47] With Dr. Rising's higher yields, the price of recombinant spider silk would be expected to be even lower at commercial scale production, with next-gen silk inching closer to price parity with the incumbents. Notably, Dr. Rising's research has also shown applicability to textile fibers - with high toughness values and a proven spinning approach.[48]

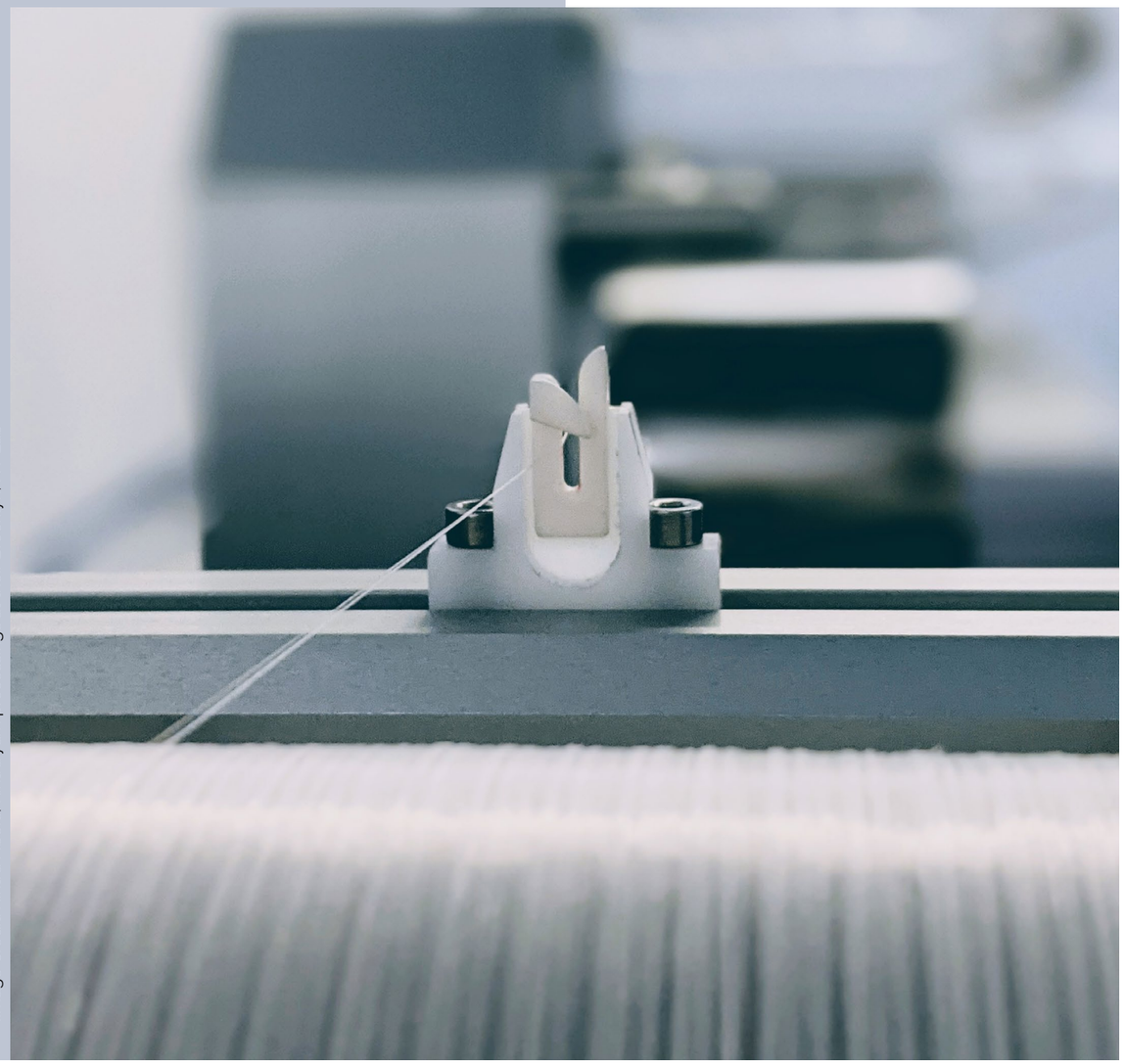


Image Credit: Kintra Fibers. Kintra yarn processings at their Brooklyn, NY Lab

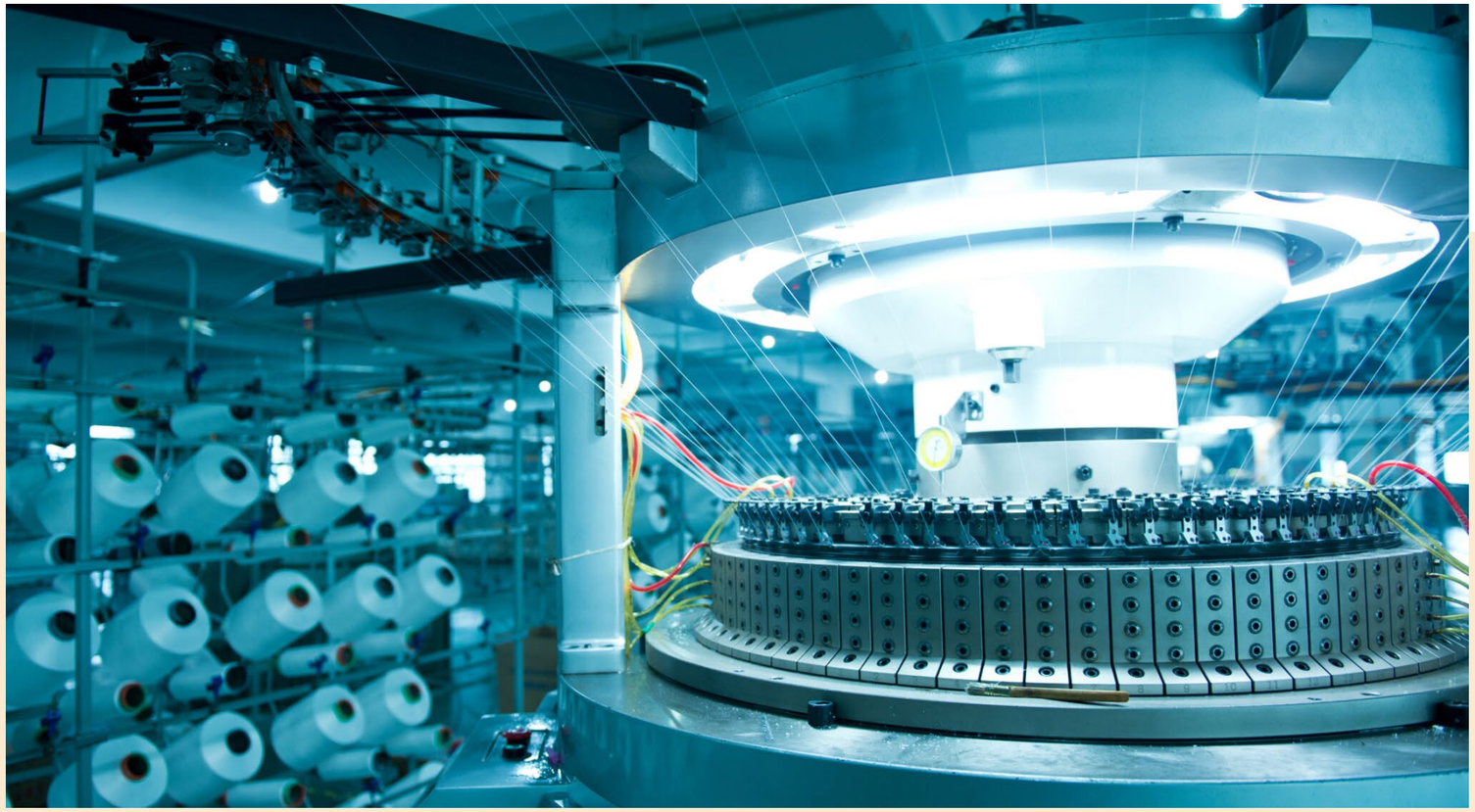



Image Credit: Spidey Tek

**SPIDEY TEK**

**Innovation Category:** Novel Protein
**Co-Founders:** Roberto Velozzi and Randy Lewis, PhD
**Founded:** 2015
**Headquarters:** California and Utah/USA

Spidey Tek's founders claim to be the first scientists to determine the molecular structure of spider silks and are early pioneers in the production of spider silk proteins. Spidey Tek implanted spider silk protein genes in the leaves of alfalfa plants in order to mass produce spider silk proteins.

The harvested alfalfa is sent through a non-polluting, eco-friendly process to extract and purify the spider silk proteins into a fine white powder and the remaining alfalfa plant waste is converted to animal feed. Alfalfa plants are replanted every 5 years, sequester CO2, and improve soil content by depositing nitrogen.

Spider silk proteins can be mixed with water to produce a wide variety of products, components and applications including filament fibers via a proprietary wet spinning process.

According to peer reviewed reports, Spidey Tek material is tougher than carbon fiber, kevlar, steel, and aluminum yet lighter and less expensive than each. It is also hydrophobic, hydrophilic, biodegradable, and has a lower environmental impact than animal-based silk. With scaling and volume it promises price parity with fibers of comparable end uses.

It can be soft-like-silk or rigid, has multi-directional or memory stretch, and can be knit or woven. It is also machine washable.

# Spiber

**SPIBER**

**Innovation Category:** Novel Protein
**Co-Founders:** Kazuhide Sekiyama, Junichi Sugahara
**Founded:** 2007
**Headquarters:** Japan

Founded in 2007, Spiber Inc. is a Japanese biotechnology company that develops synthetic protein materials without the use of animals or petroleum resources. Spiber's Brewed Protein™ can replace silk from silkworms and other animal fibers as well as petroleum-based plastic fibers.

To create their Brewed Protein™, Spiber inserts the desired protein code into microorganisms. The microorganisms grow in a bioreactor eating sugars and other nutrients such as minerals. After fermentation is complete, the protein is purified and dried into a pellet or powder. Brewed Protein™ polymer can be made into fiber, films, or material.

Spiber produces protein polymer, filament, and staple fibers in-house. The filament fibers are fine and have luster like silk. The staple fibers can deliver on a variety of end products depending on the twisting and entanglement of the yarns. They can also adjust the protein content and yarn diameter for surface texture, weight, and handfeel of yarns.

Based on an LCA study they have found Brewed Protein™ fiber can be estimated to emit fewer GHGs, requires less water and reduces land use compared to current animal agriculture once their Thai plant is fully operational. Unlike current petrochemical fibers in the market, Brewed Protein fibers biodegrade in marine environments and disintegrate in soil.

Currently, their primary focus is on textile applications for the apparel industry.


Image Credit: Spiber Inc - Various Materials

A. Brewed Protein polymer powder, fermented using microorganisms containing specially-designed DNA and fed with plant-based sugars.

B. Filament yarns produced via dissolving Brewed Protein polymer in a solvent and extruding it through a nozzle. These yarns exhibit a luster and fineness similar to silk.

C. Staple fiber: Brewed Protein filaments which have been cut into short lengths and opened into staple fibers. Fiber entanglement and fluff porosity have a large impact on the texture of the resulting material.

D. Spun yarn created by spinning with staple fibers. Changing the fiber diameter and protein content allows for a variety of textures, ranging from smooth and silky to the bulky heft of fleece.

E. Leather-like samples created by processing and shaping Brewed Protein polymer.

F. Resin produced by subjecting Brewed Protein polymer to elevated temperature and pressure in a metal mold. Brewed Protein resins can be processed into a range of shapes and forms.

Image Credit: Tandem Repeat

**TANDEM REPEAT**

**Innovation Category:** Novel Protein
**Co-Founders:** Dr. Melik Demirel, Dr. Gozde Senel-Ayaz, Dr. Benjamin Allen
**Founded:** 2017
**Headquarters:** Pennsylvania/USA

Tandem Repeat was inspired to create a new fiber after discovering the performance properties like stretch, strength, and self-healing from squid ring teeth. Silk and squid share a similar molecular architecture: both have nanoscale crystalline and amorphous parts. Tandem Repeat Co-Founder Dr. Melik Demirel began investigating whether these characteristics were transferable to other fibers and materials nearly 10 years ago. He and his team at Penn State took five years to develop their protein-based filament fiber, Squitex.

Squitex uses precision fermentation technology and can create powders, fibers, yarns, and fabric. The protein provides unique properties such as self-healing, elasticity, strength, and thermal responsiveness and can be processed through most current manufacturing equipment.

Tandem Repeat is looking into the future of molecular farming — using agricultural plants to produce Squitex fibers. Plant molecular farming has the potential for cost-effective production while reducing environmental impacts.

Squitex plans to sell fibers and finished goods.

# WHITE SPACES

MII has identified next-gen silk white space opportunities for innovators, scientists, and investors. We use the term white space to refer not only to areas without current competition, but also to new technology and gaps in existing markets.[50]

## White Space Opportunities in Silk Include:

- **Biodiscovery.** While spider silk has gained popularity as a next-gen silk target, there are many other silk-like protein fibers in nature that precision fermentation approaches could target. For example, proteins found in mussel byssal filaments, wasp silk, or squids[51] have unique properties that may replicate or exceed the attributes of silkworm silk.

- **Transform Current-gen To Next-gen.** Current-gen synthetic textiles like polyester, nylon, and cellulosics (e.g., viscose) were originally created as alternatives to animal silk. The main issue with these current-gen alternatives is their use of fossil fuels, toxic chemistries, and forest-clearing wood pulp. If innovators work on environmentally preferable alternatives to these current-gen fibers, we could fast track the path to next-gen silk.

- **Fiber Structure.** The key to mimicking silk is to make a smooth, translucent, continuous filament. Thus far, no other fiber has replicated the triangular cross-section of silk which contributes to its luster, skin comfort, and tight yarns.

- **Comfort Is Key.** Protein-based animal fibers like silk and wool are known for their unique moisture and thermal properties that make them comfortable in various weather conditions. Next-gen innovators should focus on this performance metric to ensure that their fiber feels as good as it looks.

- **Other Applications.** Next-gen silk has broad applications beyond textiles, including beauty products and cosmetic procedures, electronic and optical devices, adhesives, and engineering and aerospace composites. Most exciting, next-gen silk's biomedical applications have the potential to regenerate nerves and tissue, heal wounds, provide cancer therapy, and more. Innovators can explore these parallel applications to expand their total addressable market.

- **Environmental Impact Assessments:** There is only one public silk LCA which analyzes silk production in India despite China being the largest producer. The silk industry repeatedly cites this issue in response to environmental comparisons yet the industry also fails to produce additional LCAs. A white space research opportunity is to conduct additional environmental impact assessments comparing China produced animal-based silk and next-gen silk.

Sea Silk Made From Mussel Byssal Threads
Sea silk is an exceptionally fine, unique, and valued fabric that is made from long silky filaments (or byssi) molluscs secrete to attach themselves to the sea bed. Image: A California mussel's (Mytilus californianus) byssal threads.[52]

"Spidey Bat VTOL" drone by Spidey Tek claims that their Spider Silk exhibits a tensile strength of 40,000 MPa, which is 10 times that of natural spider silk and 100 times that of carbon fiber. Their spider silk can also provide the same weight reduction benefits that carbon fiber is reputable for.

Cleaned, combed sea silk fiber[53]

# ENDNOTES

1 International Silk Association. Only Silk is Silk. For the Student of Silk, New York, no date.

2 Alex Scott, “Spider Silk Poised for Commercial Entry,” Chemical and Engineering News, March 3, 2014. https://cen.acs.org/articles/92/i9/Spider-Silk-PoisedCommercial-Entry.html; John G. Hardy et al., “Polymeric materials based on silk proteins,” Polymer 49 (Elsevier Ltd., 2008): 4309-4327.

3 M. Senthilkumar and B.B. Jambagi, “Physical & comfort properties of spun silk knitted fabric,” Fibre2Fashion.com, April 2008. https://www.fibre2fashion.com/industry-article/3246/ physical-comfort-properties-of-spun-silk-knitted-fabrics; Karen Selk, “Reeled Silk Yarns,” Treenway silks.com, no date. https://www.treenwaysilks.com/kc-yarnsblends.php

4 A denier is a unit of measure for mass and is expressed in terms of grams per 9,000 meters.

5 A micron is a unit of measure for length. One micron is one millionth of a meter.

5 N.V. Padaki et al., “Advances in understanding the properties of silk,” Advances in Silk Science and Technology (Elsevier Ltd., 2015): 3-16. Food and Agricultural Organization of the United Nations, “Profiles of 15 of the world’s major plant and animal fibres,” International Year of Natural Fibres 2009.
http://www.fao.org/natural-fibres-2009/about/15-natural-fibres/en/#:~:text=Silk%3A%20It’s%20filament%20is%20a,diameter%20of%20 10%2D13%20 microns

6 An average human hair is approximately 100 microns.

7 Bivoltine silk is silk that is harvested twice annually. In contrast, multivoltine silk is harvested throughout the year.

8 J.E. Boyce, “Scroop, Luster, and Hand: The Science and Sensuality of Silk.” Thesis: Master of Science in Science Writing, Massachusetts Institute of Technology (2005): 25.

9 https://mainetopmill.com/blogs/news/exploring-thetechnical-side

10 Data sourced from Amrita Sarkar et al., “Chemical Synthesis of Silk-Mimetic Polymers,” Materials 12, 4086 (2019): 1-24.

11 Density is the mass of a material divided by its volume. Denser materials are heavier and are often more durable.

12 Elongation at break is a measure of how far a material can stretch before breaking.

13 Tensile strength is the amount of load or stress a material can withstand until it stretches and breaks.

14 Stiffness is the resistance of a fabric to flexing or bending.

15 Toughness is the ability of a material to absorb energy without rupturing and to resist fracturing when stressed.

16 Staple fibers may also be aggregated in mats to produce nonwovens or felts.

17 R. Sinclair, “Chapter 3: Natural Textile Fibres: Animal and Silk Fibres,” Textiles and Fashion: Materials, Design and Technology (Woodhead Publishing, 2015): 69.; N.V. Padaki et al., “Advances in understanding the properties of silk,” Advances in Silk Science and Technology (Elsevier Ltd., 2015): 3-16.

18 New Cloth Fiber, “Artificial Fiber by Biomimetics,” Fibre2Fashion.com, May 2010. https://www.fibre2fashion. com/industry-article/4841/ artificial-fiber-bybiomimetics#:~:text=Rayon%20appeared%20about%20 a%20century,(cellulose)%20as%20wood%20pulp.; Canada. ca, “Certain Azo Disperse Dyes - information sheet,” Chemicals at a Glance, Sep 5, 2020. https://www.canada.ca/en/health-canada/services/ chemical-substances/fact-sheets/chemicals-glance/ certain-azo-disperse-dyes.html

19 The term “hand” refers to the way a fabric feels when it is touched or the feel of the fabric on skin.

20 The next-gen spider silk material company Spiber noticed that spider silk dramatically shrunk when exposed to water in its early use of recombinant spider protein materials, and it subsequently redesigned its protein to reduce shrinkage. You can learn more about Spiber in the innovator profiles section.

21 Most silk is produced in China, for which there is very limited LCA information. More information can be found in the UNFCCC report on animal fiber LCAs: https://unfccc. int/sites/default/files/resource/230620%20BLS2304%20 UCC%20FC%20report%20animal%20fibres%20v03. pdf

22 Astudillo et al., Life cycle assessment of silk production - a case study from India. Handbook of Life Cycle Assessment (LCA) of Textiles and Clothing (Elsevier Ltd., 2015): 265-266

23 Ibid.

24 A material’s blue water footprint is the volume of surface and groundwater consumed during the production of the material.

25 Freshwater eutrophication refers to the excessive growth of aquatic plants or algal blooms in freshwater ecosystems, which starve aquatic organisms of the light and oxygen they need to survive. Eutrophication from silk farms occurs when high concentrations of fertilizers and manure are discharged into freshwater ecosystems.

26 Nylon 66 is a type of nylon that is commonly used in textiles.

27 Bonded labor is a modern form of indentured servitude and a violation of the Universal Declaration of Human Rights. Bonded laborers are required to work to repay a debt or loan, often indefinitely, and do not receive income from their labor.

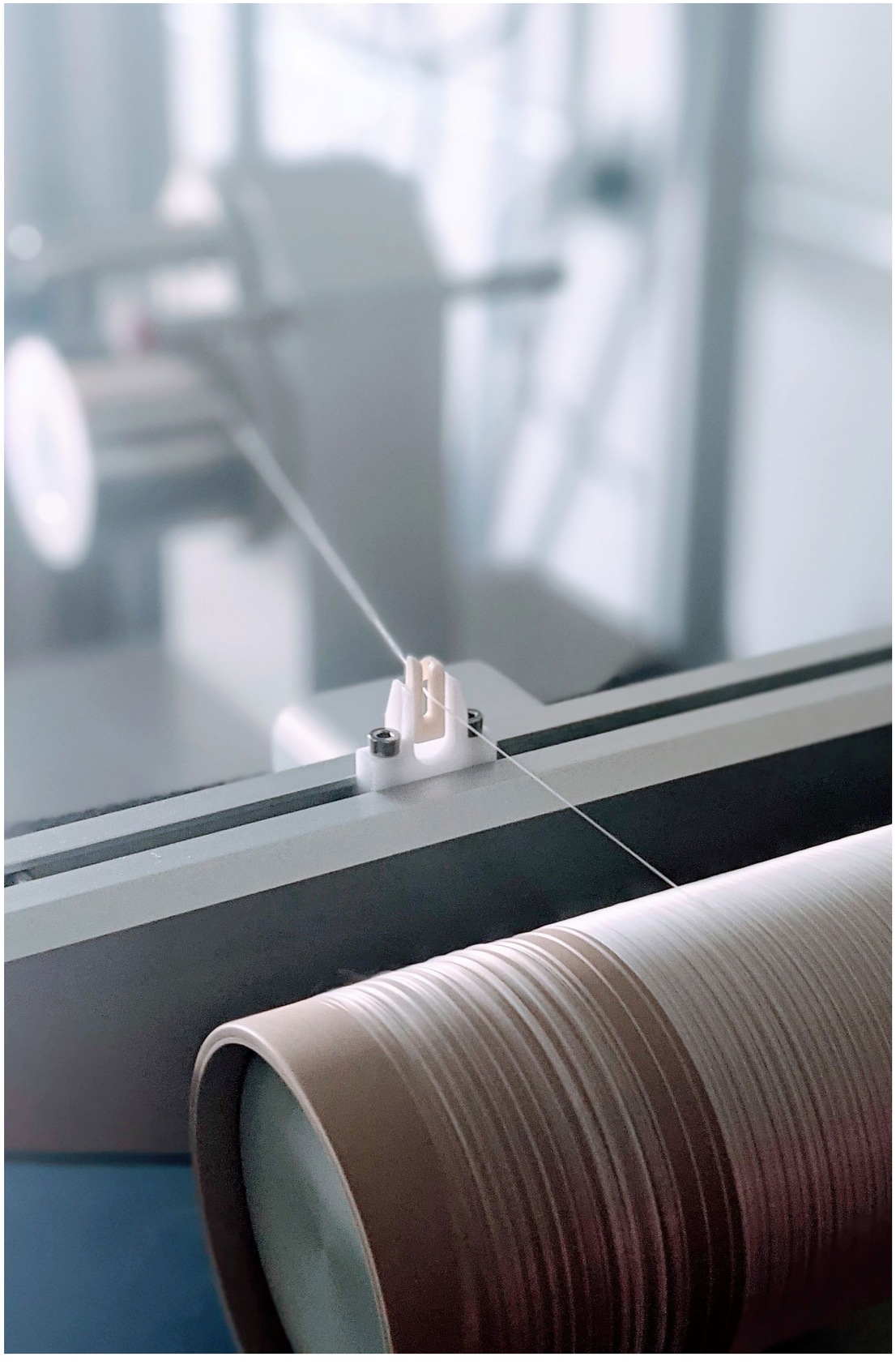


Image Credit: Kintra Fibers

Image Credit: Mara Hoffman x Circ

28 “Fibre Briefing: Silk.” Common Objective, www. commonobjective.co/article/fibre-briefing-silk.

29 Abraham Rowe, “Silk production: global scale and animal welfare issues,” Effective Altruism Forum, Apr 19, 2021. https://forum.effectiveal-truism.org/posts/ mZEuNcwTZxLnXrZR6/silk-production-global-scale-andEndnotesWhat Makes Silk, Silk? 32 animal-welfare-issues?fbclid=I-wAR3Rv6qJicvfg7J_2v60bj1V LFgJgr-EZORS2DO6BknfJskDkbCZrCs3YUM

30 “Beauty without Cruelty - India.” Bwcindia.org.

31 United Nations Environment Programme and Caribbean Environment Programme. 2015. Plastics and Microplastics - Factsheet July 2015. https://wedocs.unep.org/20.500.11822/28420

32 Barrows, A. P. W., Sara E. Cathey, and Christopher W. Petersen. “Marine environment microfiber contamination: Global patterns and the diversity of microparticle origins.” Environmental pollution 237 (2018): 275-284. https://doi.org/10.1016/j.envpol.2018.02.062.

33 Boucher, Julien, Friot, Damien. (2017). Primary Microplastics in the Oceans: A Global Evaluation of Sources. Gland, Switzerland: Interna-tional Union for Conservation of Nature and Natural Resources.

34 A keystone species is defined in the dictionary as a species on which other species in an ecosystem largely depend, such that if it were removed the ecosystem would change drastically.

35  Textile Exchange. Preferred Fiber & Materials Market Report 2022. https://textileexchange.org/app/uploads/2022/10/Textile-Exchange_PFMR_2022.pdf

36 As of 2022, annual global silk production is approximately 170,000 metric tons and annual global polyester production is approximately 61 million metric tons.
Textile Exchange. Preferred Fiber & Materials Market Report 2022. https://textileexchange.org/app/uploads/2022/10/Textile-Exchange_PFMR_2022.pdf

37 Data from 2019 for silk, from 2020 for polyester:
Emerging Textiles, “Raw Silk and Dried Cocoon Prices in China,” Emerging Textiles.com, 2019. https://emergingtextiles.com/?q=pdb&s=htm-Ltable.sample-linen-cashmere-silk-mohair-down-fiber-price-database.silk-yarn-dried-cocoon-domestic-daily-market-price-sample-table.html;
Fibre2Fashion.com, “Polyester Filament Yarn Market Report and Price Trend,” Textile Market Price Trend Report 2020. https://www.fibre2fashion.com/market-intelligence/textile-market-watch/polyester-filament-yarn-pfy-price-trends-industry-reports/5/?g-code=1

38 Common Objective, “Fibre Briefing: Silk,” Fibres & Fabrics, Feb 1, 2018. https://www.commonobjective.co/article/fibre-briefing-silk

39 Recombinant silks are produced by inserting silkworm or spider silk protein genes into host organisms such as plants, yeast, and bacte-ria. These genes instruct their host organisms to produce a particular silk protein.

40 Plant-based next-gen materials are derived from virgin or waste/byproduct plant matter. For simplicity, algae and the fruiting body of fungi are included in this category, even though they are not plants.

41 Microbe-derived next-gen materials use cellular engineering (e.g., cell culture, fermentation) to produce products such as proteins and other biopolymers for next-gen material formulations.

42 Mycelium-based next-gen materials are derived from the root-like structure of many fungal species, which is called mycelium. This cate-gory is distinctive from the plant-derived category (which includes the fruiting body of fungi) due to the rich activity of next-gen innovation involving mycelium.

43 Cultivated animal cell-based next-gen materials use tissue engineering approaches to grow animal cell constructs (e.g., skin) in the laboratory.

44 Material Innovation Initiative, Innovator Database, available at https://materialinnovation.org/next-gen-innovation-databases/innova-tors-database/.

45 “Precision Fermentation Perfected: Fermentation 101.” 2023. TurtleTree. March 6, 2023. https://www.turtletree.com/precision-fermenta-tion-perfected-fermentation-101/.

46 Schmuck, Benjamin, Gabriele Greco, Andreas Barth, Nicola M. Pugno, Jan Johansson, and Anna Rising. 2021a. “High-Yield Production of a Super-Soluble Miniature Spidroin for Biomimetic High-Performance Materials.” Materials Today 50 (Volume 50): 16–23. https://doi.org/10.1016/j.mattod.2021.07.020.

47 Edlund, Alan M., Justin Jones, Randolph Lewis, and Jason C. Quinn. 2018. “Economic Feasibility and Environmental Impact of Synthetic Spider Silk Production from Escherichia Coli.” New Biotechnology 42 (Volume 42): 12–18. https://doi.org/10.1016/j.nbt.2017.12.006.

48 ———. 2021b. “High-Yield Production of a Super-Soluble Miniature Spidroin for Biomimetic High-Performance Materials.” Materials Today 50 (Volume 50): 16–23. https://doi.org/10.1016/j.mattod.2021.07.020.

49 “Engineered Spider Silk Proteins for Biomimetic Spinning of Fibers with a Toughness Equal to Silk from Spiders | Karolinska Institutet Nyheter.” 2022. News.ki.se. March 30, 2022. https://news.ki.se/engineered-spider-silk-proteins-for-biomimetic-spinning-of-fibers-with-a-toughness-equal-to-silk?pk_vid=0d8f5a35bac46dc0169765367 97df8b0.

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

51 See Tandem Repeat’s innovator profile to learn more about its animal-free, fermentation-derived squid protein fiber.

52 S“Multimedia Gallery - Marine Life of California’s Rocky Shores (Image 19) | NSF - National Science Foundation.” 2007. Www.nsf.gov. June 20, 2007. https://www.nsf.gov/news/mmg/mmg_disp.jsp?med_id=61241&from=.

53 “Handwerkliche Aspekte.” n.d. Muschelseide. https://muschelseide.ch/handwerkliche-aspekte/.

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**About MII**

The Material Innovation Initiative is a nonprofit think tank that accelerates the development of high-performance, animal-free, and environmentally preferred materials with a focus on replacing silk, wool, down, fur, and leather and their synthetic alternatives. We advance the next-gen materials revolution by connecting science and big ideas. We focus on research, knowledge-sharing, and fostering connections to fast-track the development of environmentally preferable and animal-free materials.

We work to cultivate a global market for next-gen materials across the fashion, automotive, and home goods industries. We work for materials that can do more while requiring less of the planet, animals, and people involved at every stage.

We imagine a circular future where the default choice for your sweater, sneaker, or seat is humane and sustainable. A future where animals are allowed to live free and thrive, the planet is saved from pollution and degradation, and workers are treated fairly and with respect.

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