Spiber

Life cycle assessment of **Brewed Protein™** fiber

A cradle-to-gate comparison with cashmere and merino wool fiber production

July 2023

At Spiber, our mission is sustainable human well-being. We want our business to have a net positive impact on each part of society that it touches. For this reason, it is important that we and our customers are able to have a thorough understanding of the impact that our materials and production processes have on the environment. To that end, we have recently concluded a year-long study performed both in-house and with the help of domain experts to compare the environmental impacts of making Brewed Protein™, cashmere, and merino wool fibers. This report explains the study process, its results, and how we will use what we learned to make Brewed Protein fiber an even more compelling solution compared to existing materials moving forward. We also hope to share some interesting discoveries we made along the way about life cycle assessment (LCA) and the challenges of comparing the environmental impact of different products.

Inquiries about this study can be submitted at our online contact form at https://spiber.inc/en/contact/

Brewed Protein™

Brewed Protein materials are the protein fibers, films, and other types of polymeric materials (see Figure 1) manufactured from protein powder through Spiber's proprietary fermentation process. Made from plant-derived sugars as the primary raw ingredient, Brewed Protein materials offer a solution to address increasing market demand for biobased, biodegradable, animal-free, and plastic-free alternatives to conventional materials.

Many of the properties and characteristics of Brewed Protein fibers can be compared to animal-based protein fibers such as cashmere and wool. We see LCA as an important tool for quantifying and sharing the comparative environmental benefits of Brewed Protein materials.

Figure 1

Figure 1-1: Brewed Protein™ materials. Examples of materials that can be formed by processing (c) Brewed Protein polymer, including (a) filament, (b) staple fiber, (d) spun yarn, (e) leather, and (f) resin.

Figure 1-2: 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.

Figure 1-3: Brewed Protein filaments that are cut into short, discrete lengths. The texture of the final material is greatly dependent on the fiber porosity and degree of twisting or entanglement of the staple fibers.

Goal and scope

To carry out this first full LCA study, we partnered with experts at EarthShift Global who modeled the cashmere and merino wool fibers and guided us as we modeled Brewed Protein™ fibers. We then had our process and results reviewed in detail by a panel of three third-party experts who gave us two rounds of feedback and requested changes to improve our study in accordance with ISO 14040/14044 guidelines. Details contained in this report represent the reviewed results from the full study.

In comparing our production process to making Mongolian cashmere and Australian merino wool, we set out to understand:

- What the impacts of our current-generation Brewed Protein fiber production processes will be when they are carried out at our factories operating at full capacity
- How we compare to other leading luxury fibers
- What the priority areas are for us to improve Brewed Protein material production in order to be better for the environment

The study was carried out with the intention of sharing the results broadly, including internally with those involved in production and process development, business development, and communications, as well as externally with investors, end-consumers, our direct customers, members of the textile value chain, and the general public.

The model

Or, did you consider the diesel for the tractors and the breakroom refrigerator?

This study is a cradle-to-gate LCA, meaning it covers the environmental impacts from all activities involved in the production of our fiber, starting with the extraction of resources from nature (the cradle) through until the fibers are ready to be shipped from the factory gate. Figure 2 gives an overview of the "systems" we modeled for Brewed Protein and animal fiber production. Any wastes created are tracked until the point at which they are deposited back to the environment in a final resting place. Since we are considering an existing production system, we did not include materials used to create production facilities. We also did not include resources for non-production aspects of business operations, such as utilities used to run the farms for animal raising or resources utilized for research and development.

We did, however, consider our initial interactions with the natural world, such as extraction of fossil fuels to make fertilizer for growing feedstock sugars; extraction of water from lakes, rivers, or groundwater for processes where applicable; and consumption of hay from rangelands by goats grown in a non-farm setting. We included all impacts of farming like water and fertilizer use, and indeed the diesel for the tractors, and the process of collecting brine from the environment and processing it into various chemicals.

We also followed the outputs of all these processes, including emissions to the environment such as air emissions from our in-house fermentation and wastewater treatment tanks, emissions from the landfills our waste goes to, and emissions from the wastes created by the processes involved in producing the raw materials we use. Similarly, we worked to measure the same stages in the livestock system, from the food the animals eat to the cleaning and combing of the cashmere and merino wool staple fibers before they are sent to spinning mills. In the animal system, we also considered the other valuable products of raising livestock including milk, meat, and leather. We used the Product Environmental Footprint allocation factors to distribute the environmental burden of livestock rearing to each of the products. See the *Co-product allocation* section for more about this. However, we did not consider the inputs or outputs for processes beyond the farm or factory gate such as spinning the fibers into yarn, for reasons which we discuss in the following section.

Figure 2

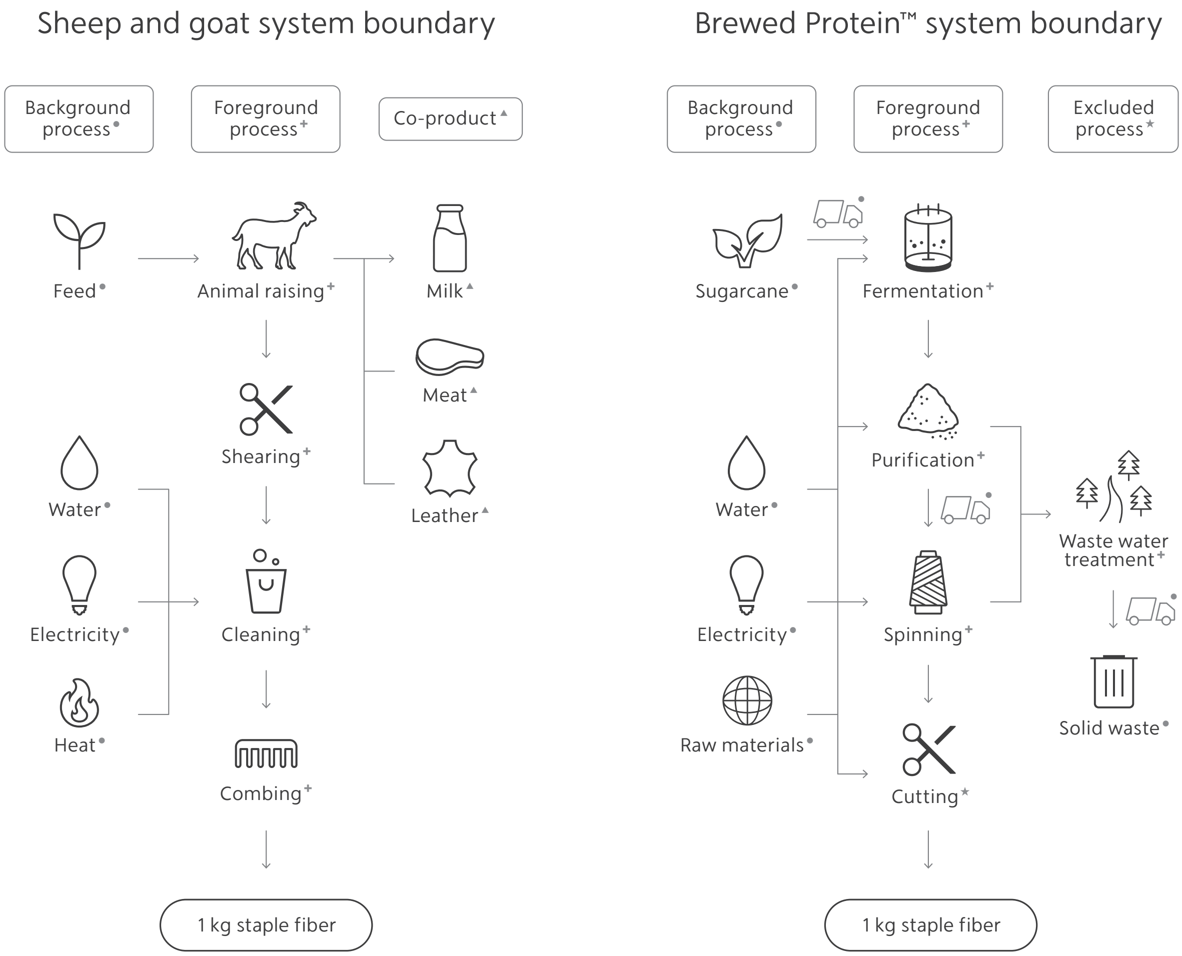


Figure 2: What was included in the model? Diagrams show the boundaries of the elements included in the model for production of cashmere and merino wool production (left) and Brewed Protein™ fiber production (right).

Why cradle-to-gate?

The impacts of garment production using cashmere, merino wool, or Brewed Protein™ fibers, as well as the impacts arising from the use of garments made from these fibers and from their end-of-life, are assumed to be the same for all three materials and are thus excluded from this comparative study. Accordingly, we chose to focus solely on the staple fiber production process in order to better understand the comparative environmental impact.

Furthermore, as we are a primarily B2B business, the companies that buy our materials can choose to process our fibers in a variety of different ways when utilizing them to produce a final garment. By providing a cradle-to-gate dataset, we can enable our B2B customers to use our results to accurately calculate the impacts of their products.

One thing that needs to be kept in mind when using cradle-to-gate impacts to plan environmental impact reductions is to avoid making choices which reduce the cradle-to-gate environmental footprint but end up causing larger footprints in the use-phase or at end-of-life. For example, it might be possible to reduce the cradle-to-gate impacts by making a product less durable, but the overall environmental burden would likely be higher.

Spiber's headquarters at the Tsuruoka Science Park in Yamagata, Japan

Limitations

What LCA cannot tell us

The underlying data

The most prominent limitation of LCA is that the accuracy of the results relies on the accuracy of the data that is used for modeling. To create an LCA model, we collect environmental impact data that corresponds to each input, output, and process within the defined system boundary. The most accurate way to obtain such data is to make actual measurements, but since that can be prohibitively expensive the most common approach is to rely on literature review or specialized databases that provide environmental impact data for LCA modeling. Our understanding of the steps required to produce animal fibers, for example, came from literature analysis by our study partners at EarthShift Global. One unfortunate limitation of this method, however, is that the data found in the literature and in databases is not always the most accurate representation of the processes that are being modeled. For example, there is much more available data for the environmental impacts of processes carried out in Europe than those carried out in Asia, so in some cases certain process chemicals are modeled using global averages rather than data corresponding to the specific region where we procure from.

Modeling a developing process

The Brewed Protein™ fiber production process comprises two main steps: producing the protein polymer and spinning it into fiber. The data for both steps was based on engineering plans for our commercial facilities before they were fully operational, so there is some additional uncertainty compared to results from data measured at an operating facility. To address this issue, we filled in any gaps using measured data from pilot-scale polymer and fiber production. While we acknowledge the limitations of relying on such early-stage data, we believe it is important for our company to begin examining production processes and their impact as soon as possible to enable us to course-correct and adopt more environmentally friendly processes at the earliest possible timing. We are now updating our models with commercial-scale production data and plan to make periodic updates to monitor progress.

Because our business plans and process optimization have been progressing quickly, this study captures a snapshot of our planned production from 2021—2022. Due to this uncertainty, we modeled several possible production scenarios and have focused throughout this report on the scenario most relevant to our current production process. Though quite similar, this scenario does not exactly match our current production setup or where we will be in the near future. For this reason, we are currently in the process of updating this study based on measured data from our current production facilities. In the meantime, however, the production processes modeled are similar enough to help us grasp the relative impacts of Brewed Protein, cashmere, and merino wool production, as well as what drives the impact of making our fibers.

Results

Brewed Protein™ fiber production has various advantages over cashmere and wool production

We primarily used two impact assessment methods: the Higg Material Sustainability Index (MSI)[2] and ReCiPe[3] methods (see the *Impact assessment methods* section and the appendix for more information). Looking at the results of the indicators used in the Higg MSI (Figure 3), Brewed Protein fiber has lower impacts than cashmere production on **climate change**, **water scarcity**, and **eutrophication**, and a similar impact on **fossil fuel depletion**. Compared to merino wool, water scarcity and eutrophication impacts are lower. The climate change impacts of Brewed Protein and wool fiber, and the fossil fuel depletion of Brewed Protein and cashmere fiber, are close enough that it is hard to say if one or the other is in fact higher or lower. Looking at these metrics, Brewed Protein fiber has a clear advantage over cashmere fiber from an impact perspective. In comparison to wool, there are some large improvements, but notably, the **fossil fuel depletion** of Brewed Protein fiber production is higher than that of wool.

When considering the more comprehensive ReCiPe impact assessment (normalized results shown in Figure 5), Brewed Protein fiber impacts are lower than those of cashmere in 13 of 18 categories, and are about the same in another two. Merino wool impacts are higher than those of Brewed Protein in 10 of 18 categories and within a 10% margin of Brewed Protein fiber values (i.e. close enough to say they are approximately the same) in another three categories.

The Brewed Protein fiber production scenario modeled here is the one we believe is most relevant to our current production methods. To see the results for other Brewed Protein fiber production scenarios, see the *Production scenarios* section below.

2. "Higg MSI Methodology Document – User Resources: How to Higg," Higg Index, https://howtohigg.org/higg-msi/higg-msi-methodology-document/, accessed August 2022

3. "LCIA: the ReCiPe Model," RIVM, https://www.rivm.nl/en/life-cycle-assessment-lca/recipe/

Figure 3

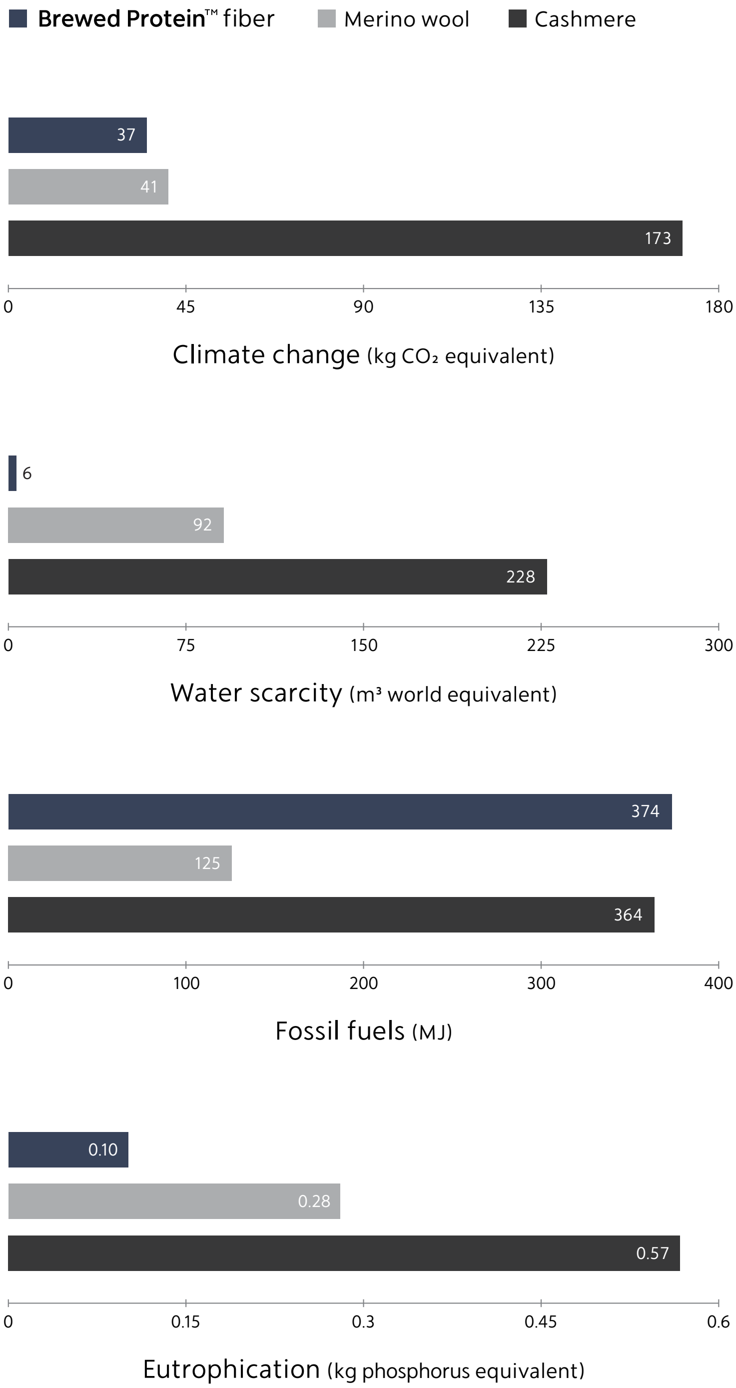


Figure 3: Midpoint results of the cradle-to-gate life cycle impact of producing 1 kg of Brewed Protein, merino wool, and cashmere fiber comparison using the impact indicators used in the Sustainable Apparel Coalition's Higg MSI assessment method.

Endpoint results

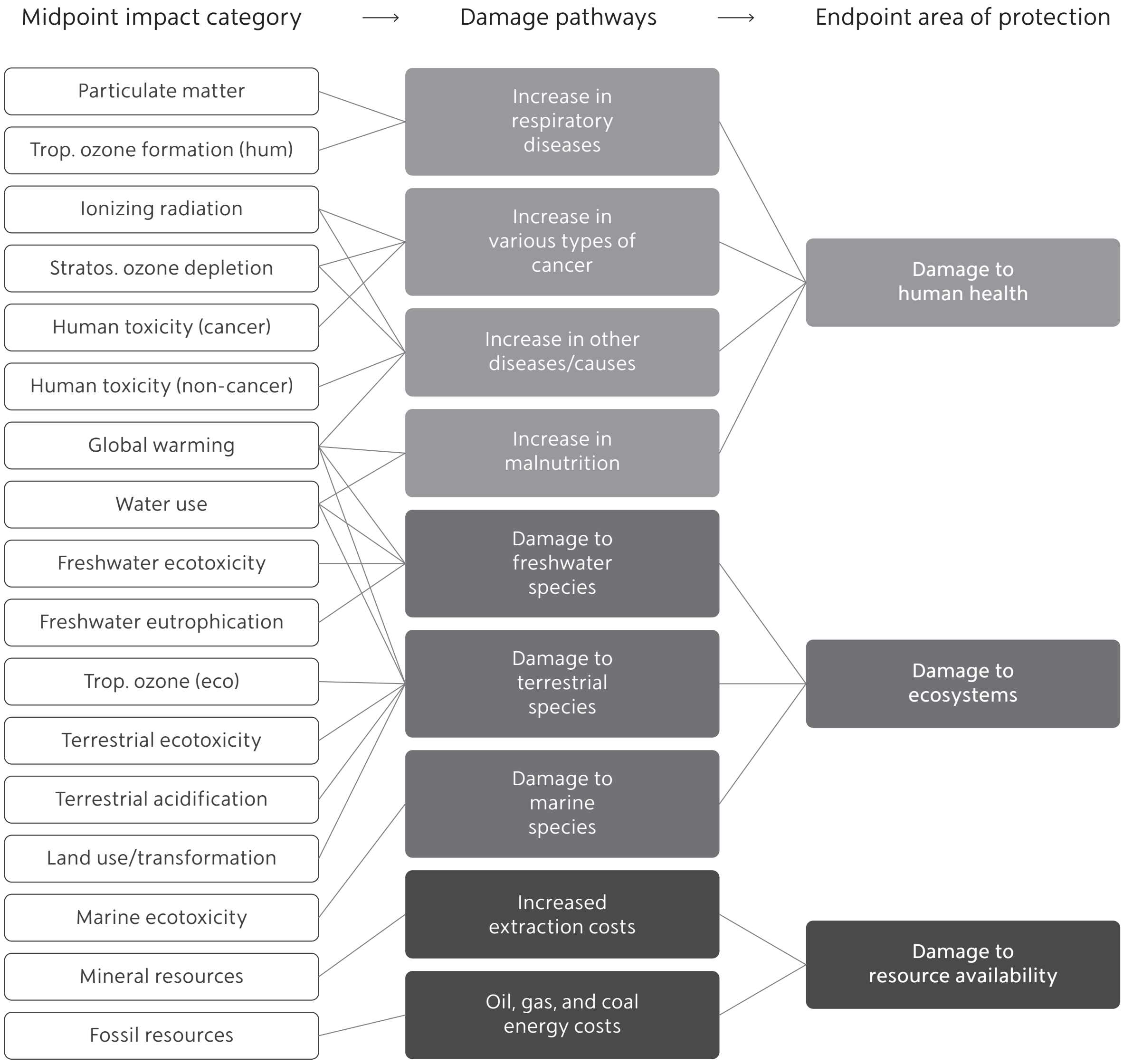
Taking a wider perspective

In LCA, midpoint and endpoint indicators are different ways of quantifying the impact of a process. Endpoint indicators consider the amount of damage done to “areas of protection,” while midpoint indicators capture a “midpoint” between an emission to the natural environment and the ultimate damage done. For example, the midpoint indicator for **climate change** is the emissions to the atmosphere of all greenhouse gasses such as carbon dioxide, methane, nitrous oxide, and others added together in units of carbon dioxide equivalents. These emissions can be measured and estimated using conversion factors determined by climate scientists to convert from units of each greenhouse gas to units of carbon dioxide, and these equivalencies are updated every few years as the scientific community’s understanding of climate science improves.

In the ReCiPe impact assessment, the three areas of protection are human health, ecosystem health, and non-renewable resource stocks. Figure 4 shows the relationship among the 18 ReCiPe midpoint categories and the three endpoint categories. Some midpoint indicators such as **climate change** impact multiple endpoints. In order to figure out how much damage is done to human health over the next 100 years because of a certain amount of greenhouse gas emissions, scientists need to do more modeling with additional assumptions. For example, the human health endpoint is measured in disability-adjusted life years (DALY). Thus, there are conversion factors in the model to put years of living with asthma and an early death from cancer into these same units. Representing these kinds of damage using a single numerical scale necessarily includes some subjective judgements. The upside of looking at endpoint indicators is that they are simpler to understand. However, because of the additional modeling required to connect a midpoint indicator to damage to human health, ecosystems, or resource stocks, the uncertainty for these results is higher.

In the comparison between Brewed Protein™ fiber, cashmere, and wool, the endpoint indicators support the same conclusions from the midpoint indicators: Brewed Protein fiber has an environmental impact advantage over cashmere in all areas of protection. Our process has 70% lower human health impact, 82% lower ecosystem impact, and 32% lower resource depletion impact than cashmere production. Compared to merino wool production, while Brewed Protein fiber production has 25% lower human health impact and 14% lower ecosystem impact, it has 95% higher resource depletion impact. The resource depletion impacts are driven by the use of fossil fuels for thermal energy and at other points throughout our supply chain, so we believe this impact will decrease dramatically as we pursue our 2035 Net Zero greenhouse gas emissions target.

Figure 4



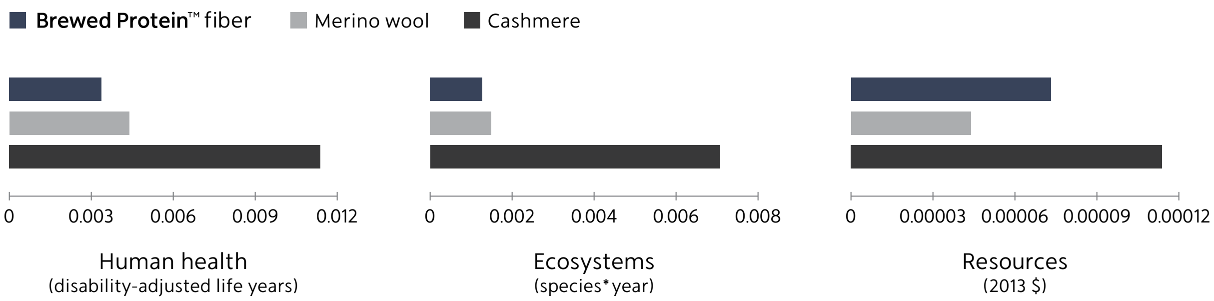


Figure 4: Endpoint analysis uses further modeling to extend the midpoint impact indicators and determines what the ultimate impacts on human health, ecosystems and resource availability would be. (upper) Connection between the *midpoints* and *endpoints*. Figure adapted from https://www.rivm.nl/en/life-cycle-assessment-lca/recipe/ (lower) Endpoint indicator results for the three fibers.

A note on the resources endpoint

While the effects of using and mishandling fossil fuels and metals can be severely detrimental to the environment, the fossil depletion and metal depletion impact indicators that comprise the resources endpoint only measure the depletion of a finite resource. The resources endpoint seeks to model the economic impact of resource scarcity as these natural resources are used. Other damage from their usage is captured in the human health and ecosystems endpoints.

Normalized results

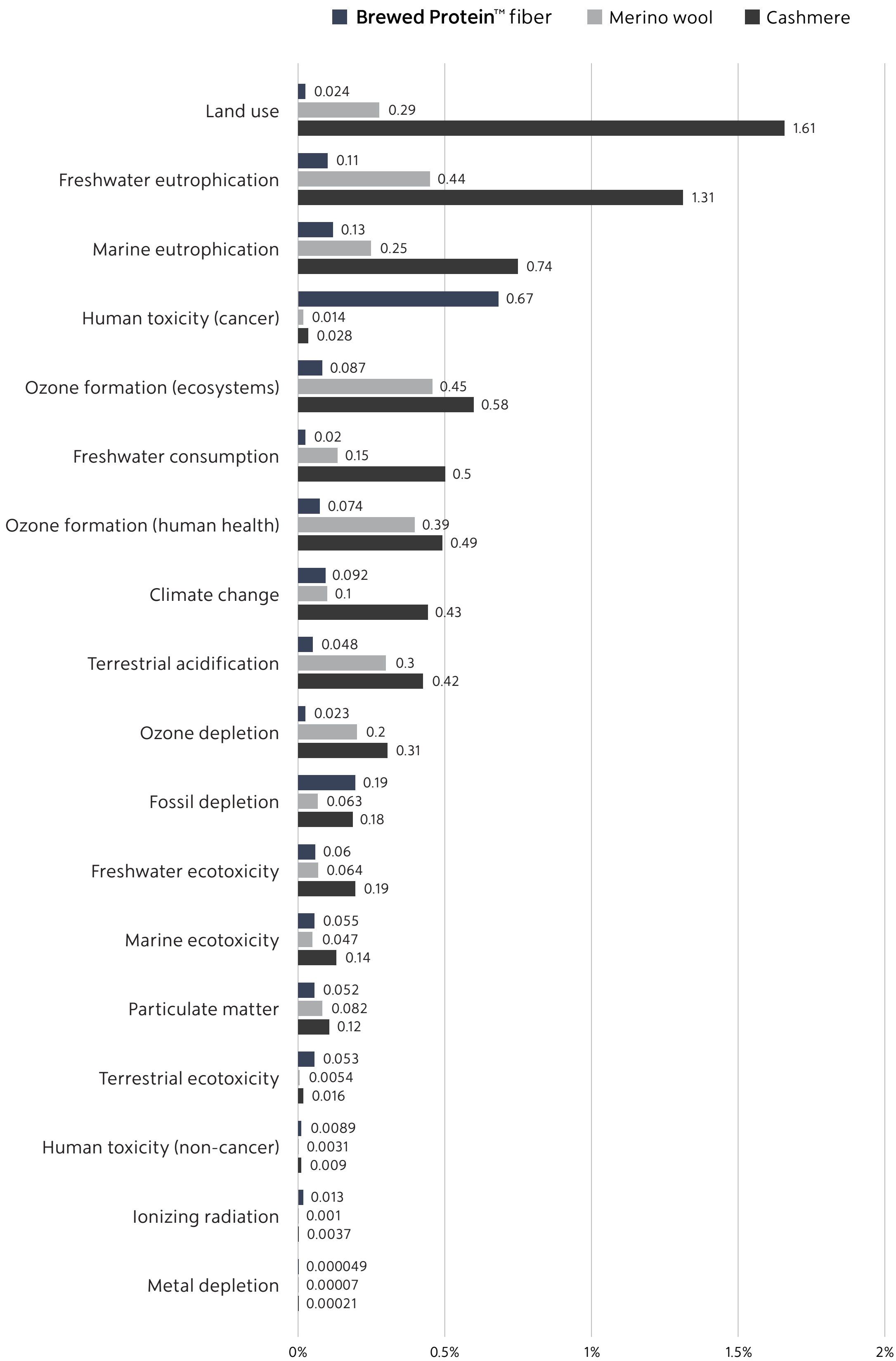
Normalized results show a variety of advantages for Brewed Protein™ fiber over the animal fibers and show us we need to focus our on-going improvement efforts on climate impacts of our process and the toxicity impacts of our upstream supply chain

Comparative LCA results can tell us how high or low the impacts of Brewed Protein fibers are in relation to those of animal fibers based on various metrics, but there may be some metrics for which all three fibers have high or negligible impacts. We can see this by looking at the impacts as a percentage of an average person's yearly impact. The developers of the ReCiPe impact assessment also provide the total global emissions and resource use of the whole human population for 2010. This allows us to look at the impacts of cashmere, wool, and Brewed Protein fiber relative to an "average" person. Figure 5 shows the impacts of 200 g, or about 1 sweater's worth, of each fiber as a percentage of the average person's yearly impact. In reality, of course, there is no such thing as an average person, and impacts vary a lot depending on where in the world someone lives. However, looking at the results in this way allows us to put the impact of our process on the scale of one person's environmental footprint, helping us to provide greater context for consumers of our products.

The results from our study show that in many categories where the three fibers have relatively higher impacts, Brewed Protein fiber performs better. We also find that Brewed Protein fiber's largest normalized impacts are in **toxicity**, **fossil fuel depletion**, and **eutrophication**. In order to reduce our impacts, we first need a better idea of what parts of our production process cause them.

Figure 5

Impacts of the fiber used to make one sweater (~200 g) as a percentage of the annual impact of an "average" person



Toxicity action plan

Results of this LCA study indicate that Brewed Protein™ production's impact for the **human toxicity (cancer)** category is higher than cashmere and merino wool. In our current LCA model, half of Brewed Protein fiber's impact in this category is driven by two chemicals used in the production process, and we plan to take the following actions:

Step 1: Update the LCA model with real production data, to make sure the usage amounts in our current model are accurate.

Step 2: Model the real sources we are buying from. For example, while most of our supply chain is in Asia, there is much more LCA background data available for Europe, so there is a geographic mismatch for some of our real inputs vs our modeled inputs.

Step 3: Investigate preferred ingredients that can be drop-in replacements for some of our high-impact ingredients. An example of a preferred ingredient is the Bonsucro-certified sugarcane sugar we are sourcing that is produced with standards for the environmental and social conditions of production.

Step 4: Explore substitutions of process chemicals to use gentler substances.

A note on personal footprint

How can you figure out your personal footprint, and what are the best ways to reduce it through personal actions and influence? For quick feedback, check out www.lifestylecalculator.com/doconomy/. When you're ready to pull out your electricity bills and get a more detailed answer, check out www.carbonfootprint.com/calculator.aspx

Contribution analysis

What causes the impact for each fiber

Supplementary feed drives the animal fiber impacts while process chemicals and energy for heating drive Brewed Protein™ fiber impact

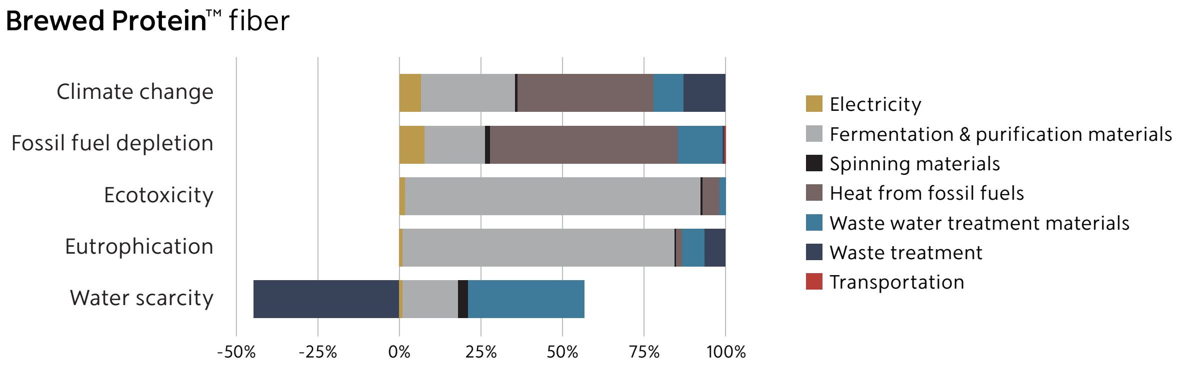
In order to better understand which parts of the animal and Brewed Protein fiber production process drive the environmental impacts, we can look at a breakdown of contributors to each impact (Figure 6).

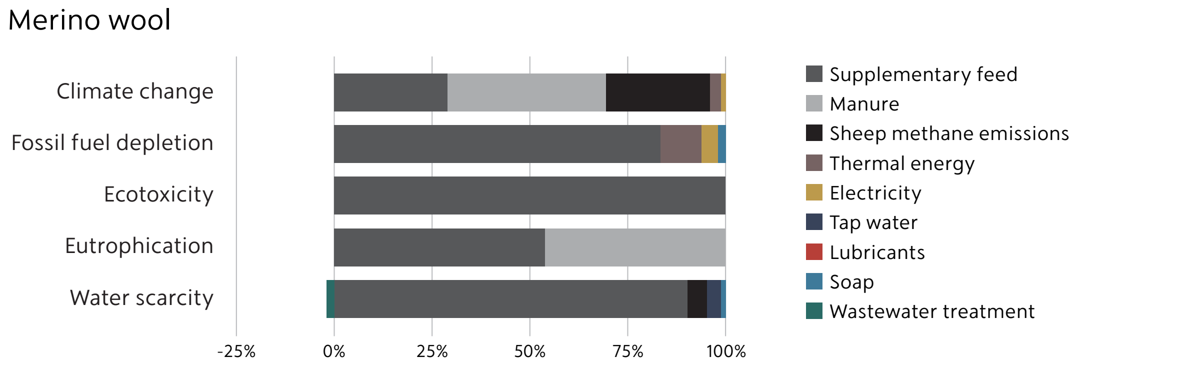
The toxicity indicators and **freshwater eutrophication** impacts are led by the upstream impacts of producing some of our process chemicals. About half of these impacts are caused by the use of just two chemicals, which allows us to prioritize them in our impact reduction efforts. We can consider alternate suppliers, alternate production methods, or substitution for other chemicals across the toxicity categories. **Marine eutrophication** impacts are driven by sugarcane sugar agriculture, but our model uses background data for conventional sugarcane production while we actually source Bonsucro[4] certified sugarcane. Bonsucro is a global voluntary sustainability standard in the sugarcane industry covering environmental and social criteria. It is also a high priority for us to engage with our sugarcane sugar supply chain members from our immediate supplier to the sugarcane farmers to both enable us to know the real impacts better but also to support decreased impacts wherever possible. For their part, **climate change** and **fossil depletion** impacts are driven by similar factors: about half of these impacts are from use of fossil fuels to generate heat for our fermentation process, and an additional 20% is from a variety of process chemicals used throughout our production process. Learning where our processes can be improved is a core reason for pursuing this LCA study of our materials, and we are eager to use this information to decrease our environmental impact.

For the cashmere and wool processes, most of the impact is from producing supplementary feed for the animals. Additionally, methane emissions from the sheep and goats, as well as emissions from their manure, are the other drivers for these animal fibers. The contribution charts seen in Figure 6 highlight the impact that the agriculture process can have in every aspect of the ecosystem. Sustainable farming or raising animals at a lower density so that less supplementary feed is required, as well as careful manure management, could mitigate some of these impacts.

4. "Bonsucro – The global platform for sustainable sugarcane," Bonsucro, www.bonsucro.com

Figure 6





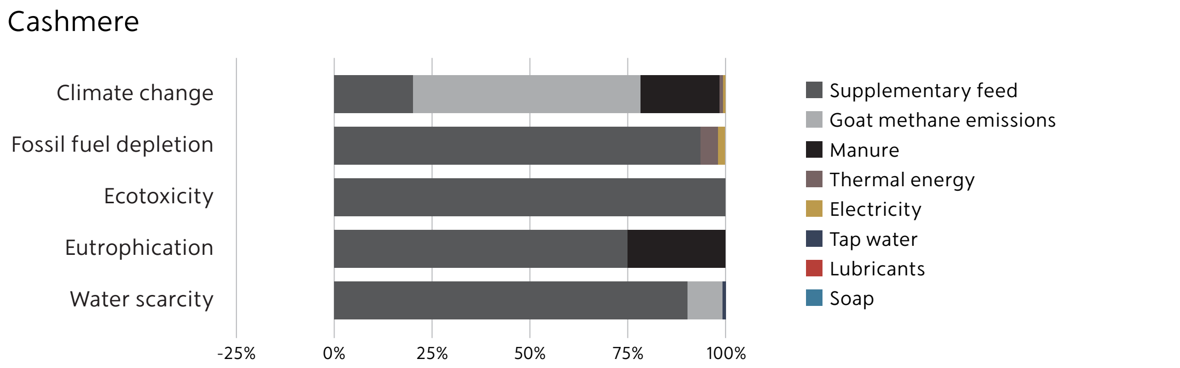


Figure 6: Breakdown of what drives the impact of the climate, fossil fuel use, toxicity, eutrophication, and water impacts of each fiber. (The negative values for water scarcity represent an environmental benefit. Specifically in this case, waste water treatment takes in dirty water and creates clean water and thus reduces water scarcity.)

Sensitivity analysis and interpretation

Some noteworthy limitations of LCA

Production scenarios

Studying a process in development

Selection of the source of electricity used for production has a significant impact on the footprint

The production scenarios included in this report are described in Table 1, and a comparison of the impacts on the Higg MSI impact indicators for each scenario is shown in Figure 7. The primary production scenario assumed in this report utilizes 100% renewable electricity and employs a resource recovery and reuse system for the fiber spinning process. Both of these are true of our actual production process as of 2023.

Comparing the various production scenarios, it is clear that use of renewable electricity is essential given the large decrease in impacts for all the Higg MSI impact indicators except water scarcity. The deployment of the resource recovery and reuse system for fiber production drives the water scarcity impact improvement and, in the case of renewable electricity use, the ecotoxicity improvement between the primary and conservative scenarios. For the other impacts and for ecotoxicity with grid electricity, the differences between the primary and conservative scenarios are within a 10% difference and thus not large enough to exceed the likely precision of the study. Ecotoxicity in the primary and conservative scenarios with grid electricity ends up the same because while the resource recovery system decreases toxicity impacts, changes in the grid-based energy inputs increase toxicity impacts.

Table 1: Description of different Brewed Protein™ fiber production processes

	Energy source	Fiber spinning waste recovery	Polymer production yield
Conservative process	Grid	No	Moderate
Primary production scenario with grid electricity	Grid	Yes	High
Conservative process with renewable electricity	Renewables	No	Moderate
Primary production scenario	Renewables	Yes	High

Figure 7

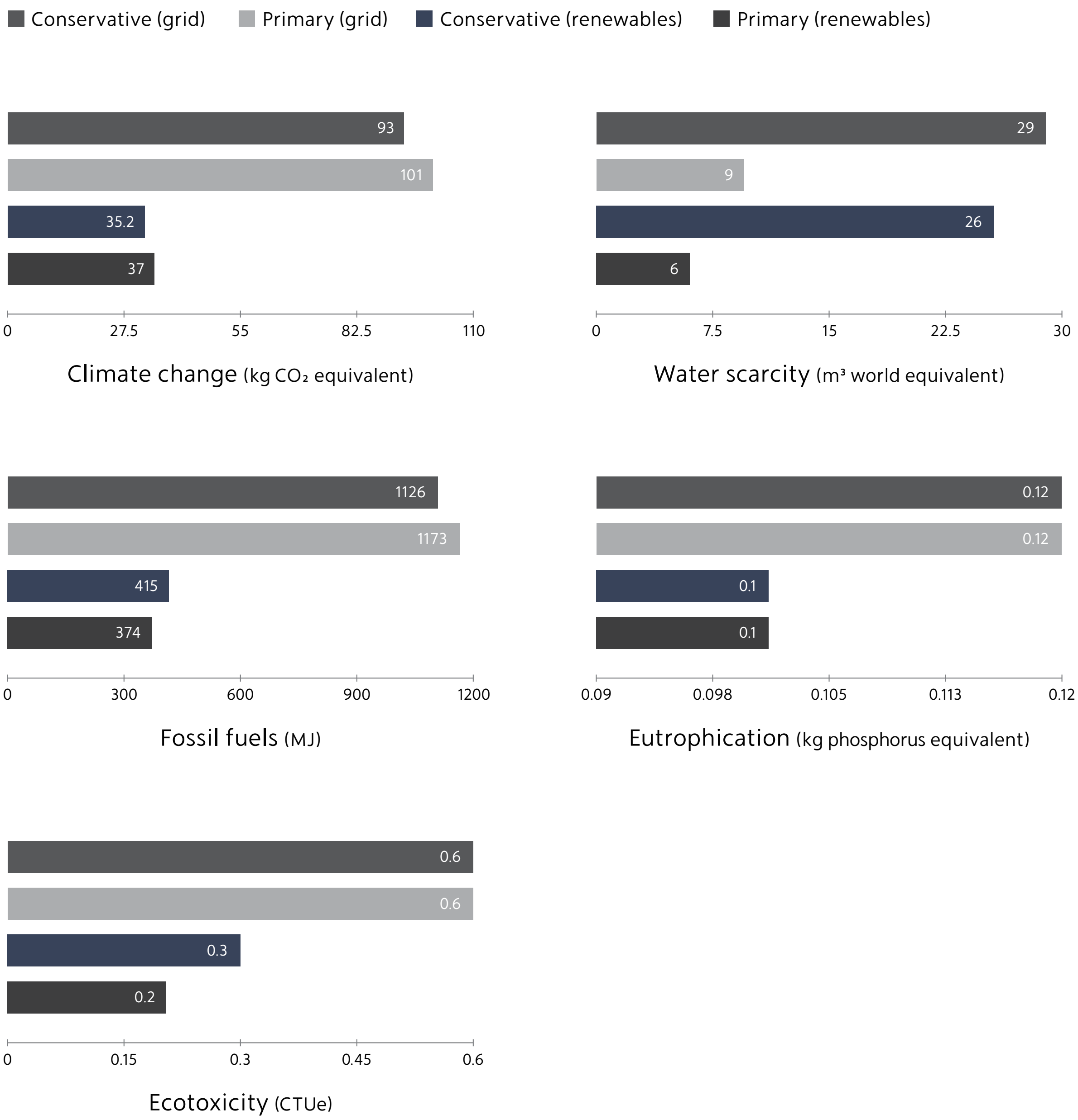


Figure 7: Impacts of different Brewed Protein™ fiber production processes. Generally, more advanced processes have reduced environmental impact.

Co-product allocation

Dividing up the environmental burden of milk, meat, leather, and fibers

There is up to a 5x difference in the climate change impact of cashmere depending on which allocation method is chosen

At present, Brewed Protein™ polymer remains the sole product of Spiber's fermentation process, but the raising of goats and sheep produces milk, meat, and leather, as well as fiber. The environmental impact of raising animals can be assigned or allocated to each product in different ways, depending on the allocation method selected. In each allocation method, cashmere fiber and merino wool get a different weight in the overall impact of animal raising (Figure 8, upper). For example, there is much more milk produced by mass than staple fiber. By cost, however, fiber is worth much more than sheep or goat's milk. For the EU's Product Environmental Footprint (PEF) method, the allocation is based on the energy the animal must use to make each of these co-products, i.e., the energy required to grow fibers, to grow their bodies, or to make milk. The allocation factors differ for sheep and goats due to the differences in size, fiber yield, and milk yield of the animals, as well as the price differences between merino wool and cashmere.

We selected PEF factors as the primary allocation method for this report, because they come from European standards which are widely used in the textile industry. All data in this report uses the PEF weighing of impacts, except in Figure 8.

Because different allocation methods can lead to very different results, and because there is no objectively correct option when selecting which method to use, the ISO LCA standards recommend avoiding allocation wherever possible. However, adopting the "system expansion" or substitution method—which involves expanding our system boundary to include the milk, meat, and leather along with the animal fibers, and then including the replacement products along with Brewed Protein fibers—also adds many assumptions given the complexity of animal rearing systems. For example, if we replaced 1 kg of merino wool with Brewed Protein fibers, the demand for lamb would need to be met by some other food source, but the result of this substitution in terms of impacts would vary greatly depending on the replacement food source chosen.

The right side of Figure 8 shows the climate change impacts of each fiber source with each allocation method. In this case, the impact of cashmere is consistently highest among the three materials regardless of allocation method. However, since there is such a large range of values, it is certainly possible that the selection of allocation methods could turn the tables in terms of the comparative advantages of one material over another. This is one reason that LCA results from different studies are hard to compare, because they may use different methods to handle co-products.

Figure 8

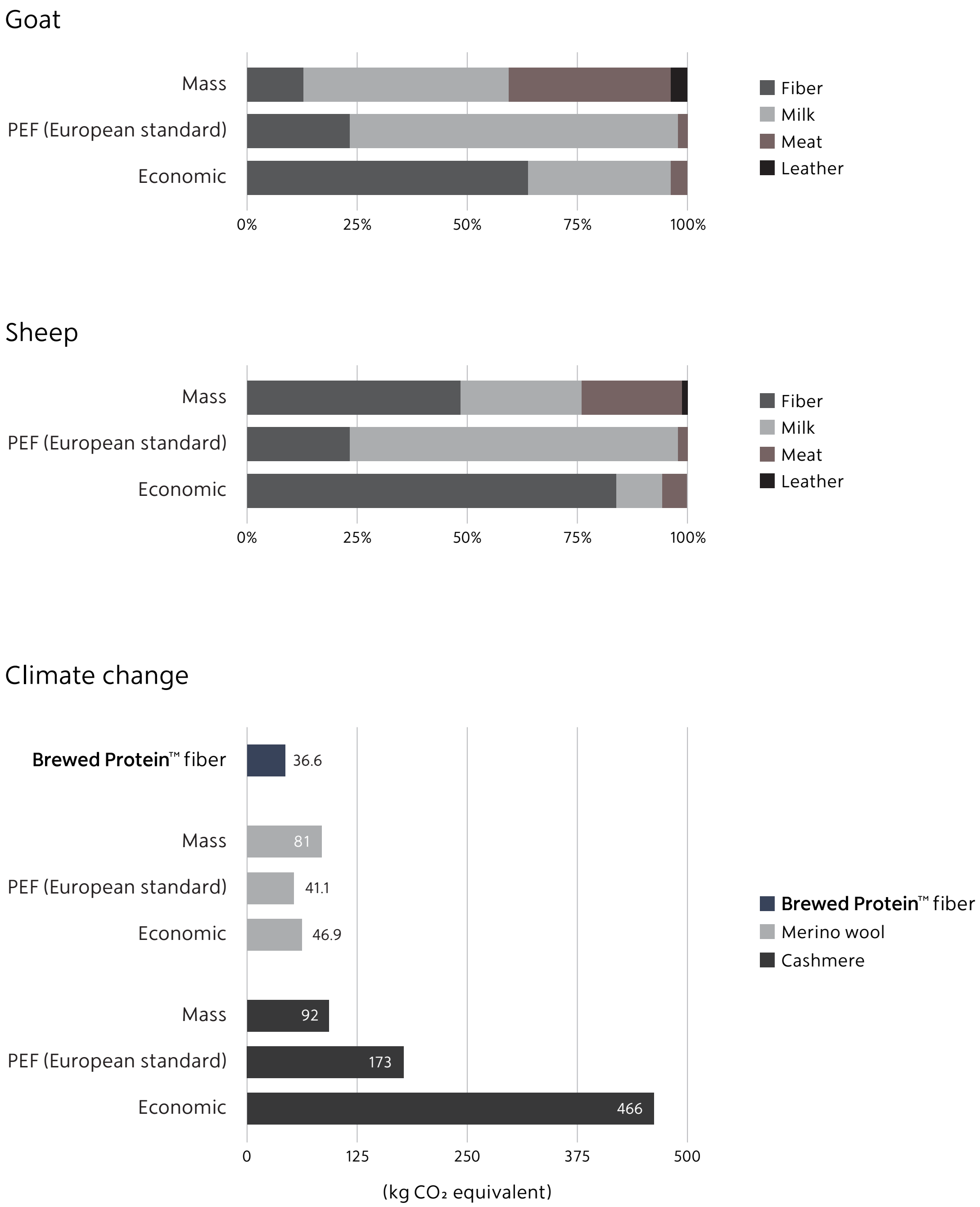


Figure 8: Allocation method. (upper) Raising goats and sheep creates multiple products. The allocation method is how the environmental impacts of raising the animal is divided among fiber, milk, meat, and leather. This can be based on the amount of each product created (mass), the value of each product created (economic), the energy required by the animal to create each product (PEF), or on yet other methods we did not consider. (lower) The climate impact of the animal fibers for different allocation methods.

Impact assessment methods

When using different assessment methods, we still get similar answers

One challenging aspect of LCA is that there are a variety of environmental impacts which are suitable targets for consideration. In this study, for example, we chose to use ReCiPe because it is well-known and considered comprehensive. However, even the ReCiPe method does not include indicators for noise, odor, or light pollution despite the fact that these impacts have been associated with health and ecosystem damage. Additionally, there are some environmental concerns, such as microplastic pollution, where scientific understanding of the damage caused is still too limited to have an agreed-upon impact assessment. Furthermore, in some cases there are multiple indicators that can be used to quantify a given impact. An example of this can be seen in Figure 9, which shows three different metrics for assessing eutrophication. The metrics might differ because their boundaries for what is included differ, or because some models are more complete or up-to-date than others in mapping emissions to environmental harm, or because they use a different midpoint[5] on the path between an emission into the environment and the ultimate harm done by the emission, e.g. to human health or an ecosystem. Thus, it is important to resist comparing results from different studies where different impact metrics (or even different versions of the same metric) have been used.

The Higg Material Sustainability Index (MSI) assessment employed in our study was developed by textile and LCA experts who focused on creating an LCA framework that would be easy to use and relevant for the textile industry. Using five metrics drawn from internationally accepted LCIA methods, the Index aims to provide a common platform that companies can use to inform material selection at the design stage. The Higg MSI was initially created by the Sustainable Apparel Coalition (SAC), which has over 250 industry members from the apparel, footwear, and home textile sectors, and is regularly referenced within the textile industry. To enable potential buyers to consider the environmental impacts of Brewed Protein™ fibers in their product development process, we used the Higg impact assessment method in this study.

We also chose to use the internationally recognized ReCiPe impact assessment, which was created through a collaboration among RIVM, Radboud University Nijmegen, Leiden University, and PRé Consultants in the Netherlands. The ReCiPe method is a comprehensive impact assessment (see the appendix for a description of the indicators), which includes midpoint indicators that model single environmental issues like climate change or eutrophication, as well as endpoint indicators that consider how each environmental issue ultimately contributes to damage to human health, ecosystems harm through species loss, and natural resource depletion, as illustrated in Figure 4.

In this case, the relative trends for the three fibers on **climate change**, **eutrophication**, **water scarcity**, and **fossil fuel depletion** impacts are the same between the Higg and ReCiPe assessments, giving us confidence in our results.

5. See p. 32 of PRé's Introduction to LCA with SimaPro for a useful illustration of the damage pathway for **eutrophication** and various midpoints that can be defined.

The path forward for Brewed Protein™ fiber production

Reflecting on the results of this study, we can see that full-scale Brewed Protein™ fiber production using renewable electricity has an advantage over cashmere fiber production in many environmental indicators, and that this advantage is quite large in some cases. Brewed Protein fiber production also enjoys an advantage over merino wool production, though not as large. In addition to the currently expected advantage with full-scale production, we expect this advantage to grow over time. The Brewed Protein production process is quite new, while wool and cashmere production have been around for thousands of years. In general, processes tend to get more efficient over time, so we expect to be able to improve our production methods in the coming years. Through company-wide initiatives and collaborations with partners in industry and academia, we are now actively exploring paths to identify and implement opportunities to improve.

Moving forward, the main areas we will be focusing on for improvements to our production process are in increasing the yield of Brewed Protein fiber relative to production inputs, and using less impactful inputs where possible—for example, using sugar from agricultural wastes.

Beyond our own production process, we plan to engage with our most impactful suppliers to understand the actual agricultural or production practices in our supply chain rather than relying on assumed global average data as we continue to study our processes using LCA. Ultimately, we hope to support decreasing the environmental impact of our whole value chain wherever we can.

Figure 9

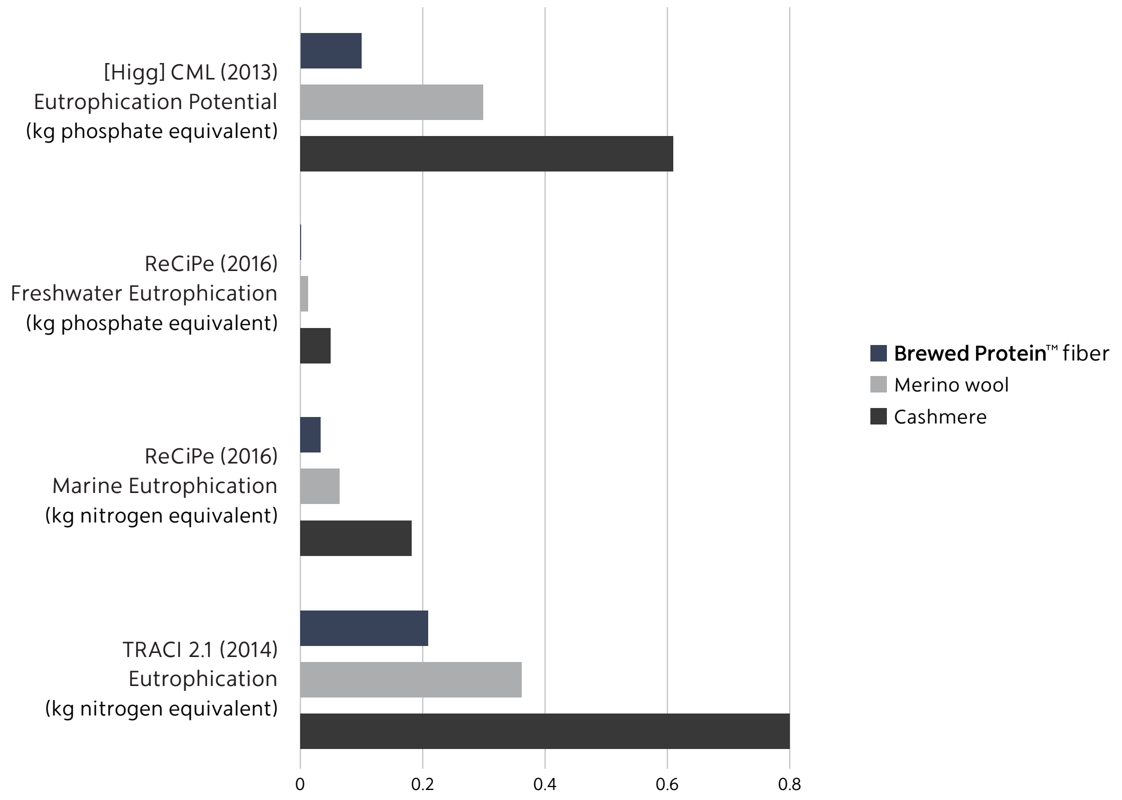


Figure 9: Eutrophication impacts of fiber production using the Higg MSI, ReCiPe, and TRACI impact assessment methods.

Eutrophication is about water quality

Seawater does not have enough nitrogen and freshwater environments do not have enough phosphorus to allow microorganisms to grow unchecked. When fertilizer runoff brings extra nitrogen to the sea or extra phosphorus to rivers and lakes, microorganisms can grow in a way that is out of balance with their ecosystems, sucking up all the oxygen in the water and creating a dead zone for creatures higher on the food chain like fish. This can lead to fishery collapse, geographically limited species extinction, and other environmental harms.

Appendix: The midpoint indicators

Climate change: This category combines the effect of the time gaseous emissions remain in the atmosphere and their ability to absorb infrared radiation. The global warming potential is measured as kg equivalents of CO_2. Biogenic carbon is not included.

Ozone depletion: A group of substances are unstable in the stratosphere where they catalyze ozone depleting reactions and reduce the concentration of beneficial ozone, resulting in increased UV radiation. Characterization factors are expressed as kg Chlorofluorocarbon (CFC)-11-equivalent.

Terrestrial acidification: Acidifying gaseous emissions of ammonia and oxides of nitrogen and sulfur adversely affect the quality of terrestrial ecosystems. Fossil fuel and biomass combustion are the main contributors of these emissions. The model calculates soil sensitivity to change in the basal saturation expressed as kg equivalents of SO_2.

Marine and freshwater eutrophication: Eutrophication is a result of increased levels of nitrogen and phosphorus in water bodies that cause excessive plant growth and then decay leading to a low oxygen environment. Eutrophication favors simple algae and planktons over other more complicated plants, causing a severe reduction in water quality. The units are kg P-equivalent for freshwater and kg N-equivalent for marine water.

Human toxicity and terrestrial, freshwater, and marine ecotoxicity: This category accounts for toxic effects of emissions to air, water, and soil, accounting for the environmental persistence (fate), accumulation in the human food chain (exposure), and toxicity (effect) of a chemical. The unit of characterization is kg 1, 4-DB-equivalent.

Photochemical oxidant formation: Photochemical smog or ground level ozone is created by various chemical reactions that occur in the presence of sunlight and negatively impacts human health and ecosystems. The primary sources of ozone precursors are motor vehicles, electric power utilities, and industrial facilities. Characterization factors are expressed as kg NMVOC-equivalent.

Particulate matter formation: Particulate matter is a collection of small particles in the air which can cause respiratory illnesses. Common sources of particulates are fossil fuel combustion, wood combustion, and dust particles from roads and fields. The characterization factor is expressed as kg PM10-equivalent.

Ionizing radiation: Measures impacts to air and water resulting from radioactivity that directly corresponds to human health. Characterization factors are measured as Uranium-235-equivalents.

Agricultural and urban land occupation: The amount of either agricultural land or urban land occupied for a certain time, measured by the area occupied for a year (m^2*yr.).

Natural land transformation: The amount of natural land transformed and occupied for a year.

Metal depletion: Measures the decrease in ore grade or ore concentration due to mining.

Fossil depletion: Measures the cumulative non-renewable energy consumption. The energy consumption is measured as kg oil-equivalents.

Water depletion: Based on the amount of freshwater consumed. It should be noted that this indicator only measures water consumption and not the environmental impacts of consumption. The unit is m^3.

Spiber Inc.
234-1 Mizukami Kakuganji Tsuruoka, Yamagata 997-0052, Japan
Contact: https://spiber.inc/en/contact/

Corporate site: https://spiber.inc
LinkedIn: https://www.linkedin.com/company/spiber-inc./
Instagram: @spiber_inc