

Perspective

Practical considerations for delivering on the sustainability promise of fermentation-based biomanufacturing

 David Lips

Spiber Inc., Kakuganji, Mizukumi 234-1, Tsuruoka 179240, Japan

Correspondence: David Lips (david_lips@spiber.inc)



Increasingly, bio-based products made via sugar-powered microbial cell factories and industrial fermentation are reaching the market and presenting themselves as sustainable alternatives to fossil and animal-based products. The sustainability potential of biotechnology, however, has been shown to come with trade-offs and cannot be taken for granted. Shared environmental impact hotspots have been identified across industrial fermentation-based products, including biomass production, energy consumption, and end-of-life fate. Based on both these patterns and our direct experience in preparing for the commercial-scale production of Brewed Protein™, we outline practical considerations for improving the sustainability performance of bio-based products made via industrial fermentation.

Introduction

Industry's growing capacity to engineer biology is increasingly being leveraged to produce novel bio-based products using sugar-powered microbial cell factories and industrial fermentation. Various companies are at or near commercial-scale production of these products, with applications ranging widely and encompassing industries ranging from food and medicine to fuels and materials [1–3].

For non-therapeutic applications in particular, sustainability performance is often presented as a key benefit of these products. The sustainability potential of biotechnology, however, has been shown to come with trade-offs and cannot be taken for granted [4].

A recent review of published life cycle assessments (LCA) for various fermentation-derived products showed highly varied environmental performance outcomes compared with fossil alternatives, with better or worse performance depending on the impact metric in question [5]. Importantly, this review also revealed shared hotspots that represented significant environmental impact drivers, including biomass production, energy use during manufacturing, and end-of-life fate. Although the specific environmental impacts and their magnitude for a given product should be evaluated in detail by conducting an LCA study, these hotspots likely apply widely to bio-based products produced via industrial fermentation. This means that for biomanufacturers prioritizing sustainability performance, extra measures are potentially needed to mitigate these trade-offs.

Based on these patterns and our experience in preparing for the commercial-scale production of Brewed Protein™ (Figure 1) as Spiber Inc. — a Japanese biotechnology company developing recombinant structural protein materials for the apparel and various other industries [1] — we outline practical considerations for improving the sustainability performance of bio-based products made via industrial fermentation.

Biomass production

Rather than raising animals or processing petrochemicals, much of the industrial fermentation industry is fueled by plant-based sugars, typically derived from renewable biomass in the form of food crops like corn and sugarcane [6].

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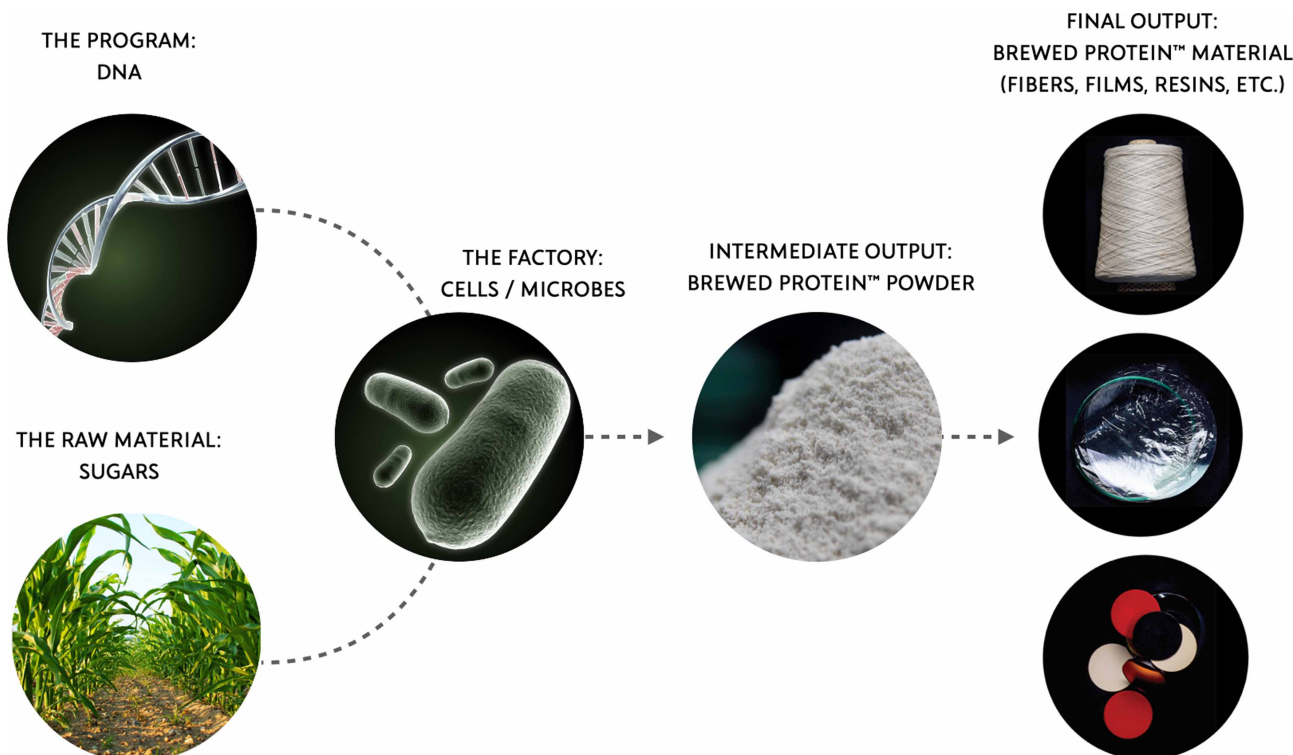


Figure 1. Spiber Inc's Brewed Protein™ production process involving genetic engineering of a microbial host to produce a target protein, fermentation of sugars from renewable biomass, and processing of resultant protein into a variety of materials.

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But as seen in the context of industrial-scale bioethanol production [7,8], the reliance on first-generation biomass poses various environmental trade-offs related to industrial agriculture, including increased land use [9], eutrophication due to fertilizer usage [10], and soil depletion resulting from high tillage farming and leaving fields fallow post-harvest [11]

To minimize land use and avoid competition with food resources, lignocellulosic biomass from crop residues can potentially be used as a feedstock source instead. But unlike sugar cane sap or the starchy parts from corn, lignocellulose has been designed by nature to resist deconstruction. This makes its efficient utilization difficult. The technical challenges to overcome this recalcitrance are multi-faceted, and include the cost-effective conversion of lignocellulosic biomass into fermentable sugars via physicochemical pretreatment and enzymatic hydrolysis, as well the engineering of expression hosts that can efficiently utilize the resulting mixed sugar streams while displaying sufficient tolerance to inhibitor compounds that may form during pretreatment [12]. Although Spiber Inc. is investing in the R&D efforts necessary to cost-effectively produce Brewed Protein™ from such lignocellulose-derived sugars, currently planned commercial facilities will, at least initially, operate on sugars derived from first generation. It is therefore important to ensure that first-generation biomass used in current commercial-scale fermentation processes is grown sustainably.

Perhaps the most efficient way to do so is by adopting voluntary sustainability standards (VSS), enforceable principles with measurable criteria to promote sustainability outcomes. Typically, VSS systems are administered by NGOs, who grant producers certification and assess compliance via independent verification systems.

To illustrate, Spiber Inc. is a member of Bonsucro, one of the fastest growing VSS providers with 5.8% of global sugarcane area certified under its system as of June 2021 [13]. Global compliance with all Bonsucro standards would reduce irrigation water use by 65%, eutrophication potential by 34%, and GHG emissions from cultivation by 51%, with most of the benefit coming from targeting the 10% of global cane production area furthest from complying with Bonsucro's criteria [14]. Simply by procuring feedstock from suppliers that are certified by Bonsucro, or by another high-quality VSS provider, biomanufacturers can likely improve the performance of their operations across a range of environmental and socio-economic impact metrics.

In the case of Bonsucro, however, certification currently requires compliance with a set of core indicators as well as a certain percentage of non-core indicators [15]. The prevention of sugarcane cultivation on land with high conservation value and limitations on the application of agrochemicals, for example, are part of Bonsucro's core indicators, while best practices in terms of efficient fertilizer application, water usage, and soil carbon improvements are part of the non-core indicators. This could result in producers not complying with various environmental criteria important to the biomanufacturer. We therefore recommend direct confirmation of VSS compliance details with suppliers and the implementation of additional sustainable agriculture practices where gaps between sustainability targets and VSS scheme requirements are identified — e.g. by planting cover crops in areas where soil quality is degraded [16], or integration of strips of native prairie species amongst biomass crops to improve biodiversity [17].

Powering the facility

Electricity consumption during the manufacturing process is a major environmental impact driver, with geographical differences in electricity grid mixes making up much of the variability in total GHG emissions [5,18,19].

This is partly due to energy-intensive commercial-scale fermentation processes such as agitation and cooling of large fermentation vessels and, often, a waste-water treatment step [20].

To overcome the related environmental impact burden, the production location is ideally chosen such that renewable energy can be used to power fermentation facilities and downstream processes. In case the location is fixed, and the available grid does not include renewable energy options, renewable energy capacity can be installed directly on-site if land is available.

If there is truly no alternative to fossil-powered fermentation, investments in market-based environmental attribute certificates or carbon offsets could potentially help reduce emissions on a net basis. The market for these instruments, however, is marked by high variability in both types of offsets and their environmental integrity. In fact, studies have shown that many investments in environmental attribute certificates do not increase the actual amount of renewable energy generation [21,22], and that many carbon offsets over-credit the amount of offsets generated [23].

Biomanufacturers seeking to offset manufacturing-related GHG emissions should therefore take extreme care in ensuring the environmental integrity of their investment, for example by coupling their credits to an underlying wholesale virtual power purchase agreement (VPPA) that results in new project financing, or by investing in vetted carbon removal projects with proven additionally.

Notably, there are potential synergies here with biomass production, particularly in the area of soil carbon storage where protocols are currently under development that would enable offsets to be generated from agricultural practices that capture carbon into the soil [24].

Responsible end-of-life

The increasing use of bio-based products in consumer-facing applications will result in the End-of-Life (EOL) fate of those materials — reuse, recycling, landfilling, composting, etc. — exerting a significant influence on sustainability.

Although the range of EOL options and their environmental impact depend largely on the specific product, consumer behavior, and geographical and cultural waste treatment patterns [25], whether or not a material can readily biodegrade in the natural environment is a key starting point for further considerations around appropriate end-of-life processing.

In Spiber Inc's case, its Brewed Protein™ polymers consist of the 20 standard amino acids found in nature. Even though these amino acids can be metabolized to inorganic compounds by microorganisms, the timely cleavage of peptide bonds in a macro-scale recombinant structural protein material cannot be taken for granted [26]. Biodegradation studies therefore have to be conducted in order to verify the degradation potential and speed in the natural environment. A study on compression-molded sheets [27] made from Spiber's Brewed Protein™ using soil-based inoculum shows quick degradation to oligopeptides and amino acids. Furthermore, biodegradation of Spiber's Brewed Protein™ fibers in seawater shows a fast and high level of mineralization, comparable to the known biodegradable compound succinic acid over 40 days (Figure 2), suggesting high ultimate biodegradability in marine conditions.

These evaluations will inform the environmental impact of various EOL scenarios (e.g. composting vs. landfilling), with the aim to establish responsible EOL policies and collection systems for specific product

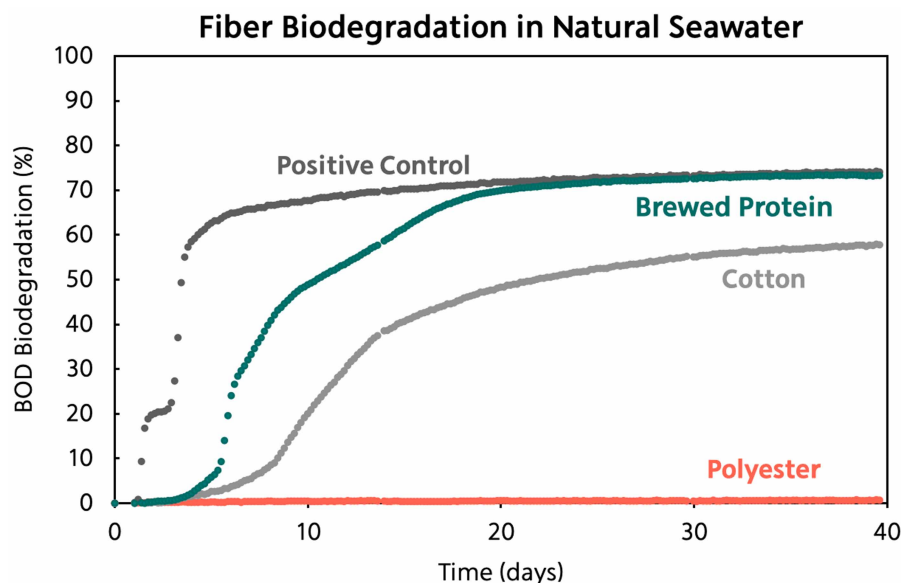


Figure 2. Comparison of Biochemical Oxygen Demand (BOD) biodegradation of succinic acid (positive control), Spiber's Brewed Protein™, cotton and polyester fibers, tested using natural seawater in accordance with ASTM D6691 using an OxiTop system.

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formulations. Similar studies to inform appropriate end-of-life treatments are likely appropriate for all bio-based products that may end up in the natural environment at the end of their life cycle.

Conclusion

Although humans have been harnessing the power of microbial cell factories and fermentation for millennia, new fermentation-based products are increasingly becoming available in a consumer-facing commercial context. The promise and expectation is that their application will contribute to environmental sustainability across a range of impact metrics while meeting society's growing demand for food, fuels, and materials.

Although there is potential to meet these expectations, scaling up fermentation-based production comes with a set of shared sustainability challenges and trade-offs that should not be ignored. Fortunately, a bio-based product's environmental impact is not a fixed outcome. Decisions regarding feedstock sourcing, energy procurement, and EOL policies all have the potential to significantly impact the environmental performance of bio-based products. As biomanufacturers, we believe it is therefore important to go beyond the 'Bio is always better' mantra, to analyse and acknowledge environmental trade-offs, and to take the extra steps required to truly fulfill our sustainability promises.

Competing Interests

The author is an employee of Spiber Inc.

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Abbreviations

EOL, end-of-Life; LCA, life cycle assessments; VSS, voluntary sustainability standards.

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