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Economic feasibility and environmental impact of synthetic spider silk production from escherichia coli

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Abstract

Major ampullate spider silk represents a promising protein-based biomaterial with diverse commercial potential ranging from textiles to medical devices due to its excellent physical and thermal properties. Recent advancements in synthetic biology have facilitated the development of recombinant spider silk proteins from *Escherichia coli (E. coli)*. This study specifically investigates the economic feasibility and environmental impact of synthetic spider silk manufacturing. Pilot scale data was used to validate an engineering process model that includes all of the required sub-processing steps for synthetic fiber manufacture: production, harvesting, purification, drying, and spinning. Modeling was constructed modularly to support assessment of alternative downstream processing technologies. The techno-economic analysis indicates a minimum sale price from pioneer and optimized *E. coli* plants of $\$761\,kg^{-1}$ and $\$23\,kg^{-1}$ with greenhouse gas emissions of $572\,kg\ CO_{2\text{-eq.}}\ kg^{-1}$ and $55\,kg\ CO_{2\text{-eq.}}\ kg^{-1}$, respectively. Elevated costs and emissions from the pioneer plant can be directly tied to the high material consumption and low protein yield. Decreased production costs associated with the optimized plant includes improved protein yield, process optimization, and an N^{th} plant assumption. Discussion focuses on the commercial potential of spider silk, the production performance requirements for commercialization, and the impact of alternative technologies on the system.

Introduction

Spider silk has extraordinary properties, including strength to weight, toughness, elasticity, mechanical vibration damping and electrical conductivity [[1], [2], [3]]. Additionally, spider silk is hypoallergenic making it more biocompatible and a promising material for a variety of products ranging from the medical to textile industries [4,5]. However, industrial production of spider silk fibers has been limited.

Spiders are cannibalistic and territorial, which makes farming a difficult operation [6]. These challenges have driven research in the area of transgenic manipulation, where the spider silk proteins can be synthetically created and harvested. Advances in synthetic biology have facilitated the production of recombinant spider silk proteins (RSSPs) in alfalfa, goats, mice, *Escherichia coli (E. coli)*, silkworms, yeast, tobacco and potatoes [[7], [8], [9], [10], [11]]. Of these methods, field experts previously suggested that transgenic silkworms represented the only economically viable pathway for the production of spider silk [12,13] but do not support this with economic modeling. Further, spider silk from transgenic silkworms is limited to fiber production. Other synthetic protein production methods allow for the harvesting of raw protein, which is a more versatile material, allowing for the creation of diverse products. The silk's extraordinary properties are directly related to the structure of the large proteins (250–350 kDa) [2,14]. Laboratory RSSPs from *E. coli* have been found to maintain a relatively large structure (>75 kDa) which is required for high strength [9]. For these reasons production through *E. coli* has significant advantages over other media.

As a raw protein, spider silk is suitable for numerous industries and can compete with many other high strength materials such as Kevlar, carbon fiber, stainless steel, aluminum, polypropylene and others. The raw major ampullate spider silk (MaSp) protein can be dissolved in water and formed into countless products including films, gels, coatings, fibers, adhesives and more [15]. Small amounts of the MaSp protein give nylon threads increased stiffness and tensile strength at concentrations of less than 5% [16]. The ability to be mixed with other materials makes it appropriate for several medical purposes such as time-release drug implants and anti-fungal coatings, both of which have been preliminarily verified [15,17]. Laboratory fabrication of silk and its derivatives are labor and material intensive, leading to high costs. This has supported the conclusion that most of the current laboratory production methods are not commercially viable. In the medical industry, where only small material quantities are used, price is less consequential than in other industries and spider silk based products may still find great acceptance. Aerospace projects, which are highly weight dependent, often rely on expensive materials to meet their high-strength lightweight needs. Currently, there are at least three companies that have publicized scale-up efforts to produce spider silk proteins via fermentation. However, at best they have shown either prototype garments or very small run small products (e.g. ties) indicating major scale-up has not yet occurred. In spite of the range of projects that could benefit from spider silk, even at high costs, the sustainability through techno-economic analysis (TEA) and life cycle assessment (LCA) of large-scale spider silk fabrication has not been analyzed and reported.

The purpose of this work is to identify the industrial feasibility and environmental impact of large-scale synthetic spider silk production through multiple production pathways. Laboratory data was leveraged in combination with an engineering process model to characterize large-scale manufacturing. The engineering process model was constructed modularly to support the assessment of alternative processing technologies. The model served as the foundation for evaluation and focuses on identifying the sustainability of the processes through the metrics of economic viability and environmental impact. Multiple scenarios are evaluated and include pioneer, substitute technology scenarios and optimized cases. The baseline pioneer plant is built on *E. coli* production and considers the effect of a low but demonstrated productivity, as well as the use of the more proven yet more costly processing methods. Alternative processing techniques are considered independently on the metrics of economic impact. An optimized case, which considers the benefits of all the alternative technologies, high protein yield and technology maturation is also analyzed. Goat and alfalfa silk production are modeled using the same downstream processing methods as used with *E. coli* production. Modeling results identify key areas for research and development to support driving to a commercially viable production platform. Discussion focuses on the potential of the various modeled pathways, sensitivity analysis to model inputs, exploration of the potential of substitute technologies and the importance of protein expression.

Section snippets

Materials and methods

Laboratory data provided the foundation for the validation of the engineering process flow and system model. While the process described has not been demonstrated commercially as a whole, multiple unit operations currently exist on a commercial scale and thus robust economic and performance data for modeling was easily obtained. The system model was modularly constructed to facilitate the analysis of alternative processing methods in an effort to evaluate emerging as well as established...

Results and discussion

Economic and environmental results are provided for multiple scenarios including a baseline *E. coli* pioneer plant (Case 1), variations of the Case 1 (a–g) presented in the Supplementary material, and an optimized plant (Case 2). Environmental impact results for Case 1 and Case 2 with resolution at the sub-process level are presented....

Conclusions

This work has directly evaluated the economic viability of the production of synthetic spider silk proteins through *E. coli*. Experimental data was used to validate sub-process models that are integrated into an engineering system model. The engineering system model serves as the foundation for sustainability assessment through TEA and LCA. Through modeling, an estimate of $\$23\,kg^{-1}$, were obtained for silk from optimized *E. coli* from an optmized large-scale prodcution facility. Emissions from *E*....

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