Determining the Environmental Benefit of Artificial Spider Silk Products

A.Y. Lauterbach* and T. Scheibel*

*University of Bayreuth, 95447 Bayreuth, Germany
anja.lauterbach@bm.uni-bayreuth.de
thomas.scheibel@bm.uni-bayreuth.de

ABSTRACT

Spider silk is a highly interesting material with outstanding properties. Since natural spider silk is not available for technical applications in large yields, the production of recombinant spider silk has been established. Here, this production process is ecologically evaluated by comparative life cycle assessment to identify the potential of artificial spider silk products to replace other polymer products. Amongst different technical applications, we focused on replacing polyamide 66 in an airbag.

Whether a product is more sustainable when using spider silk rather than an existing polymer can only be answered with thorough examination. The methodical approach outlined here allows direct influence of further process developments towards more sustainable solutions and thereby improving future products.

Keywords: recombinant spider silk, comparative life cycle assessment, LCA

1 INTRODUCTION

Most spiders are cannibalistic, and farming is therefore not possible, a problem which has prohibited technical applications in the past. Nevertheless, the production of recombinant spider silk is feasible [1], [2]. Applications are possible for silk fibers but also for non-natural silk structures like nonwoven meshes and films [3], [4], [5], [6], [7].

Many biotechnological processes have already been investigated for their ecological potential, like for example the manufacture of a complex molecule like riboflavin (vitamin B2) and base chemicals like acrylamide or acrylic acid, where the biotechnological processes proved to be superior to the chemical ones [8], [9]. The case studies of these products showed a reduction of some or all of the energy use, water use, wastewater or greenhouse gas emissions. In contrast, the case study of fermentation derived polyhydroxyalkanoates (PHA) did not show favorable effects towards more sustainable products [10]. However, no reliable comparison can be drawn between these processes and the production of recombinant spider silk and resulting products.

The potential of artificial spider silk products to replace other products can be evaluated using comparative life cycle assessment, taking into account the production of all raw materials, the supply of energy and the disposal or recycling of the product. Here, we focused on a technical application that could be realized with spider silk replacing the typically used polyamide 66 in an airbag [11]. Polyamide 66 fibers are characterized by a high breaking strength and elasticity as well as high abrasion resistance and melting temperature. This is crucial for application in an airbag because of the fast inflation and the high collision impulse involved. Spider silk fibers feature even superior properties in comparison to Polyamide 66 (Table 1). Therefore it is worthwhile to begin an ecological product evaluation of the use of spider silk in an airbag.

1.1 Production of Recombinant Spider Silk

Biotechnological production of recombinant spider silk is accomplished using a genetically modified strain of the microorganism *E. coli* via fermentation in a defined culture media. Subsequently, the bacteria are separated from the media by centrifugation, and the cell walls are disintegrated by a high pressure homogenizer. The cell debris and the insoluble target protein are separated from the soluble fraction via filtration. The cell debris is then solubilized and separated from the target protein. Urea is added to the solution, and the remaining impurities are dissolved and subsequently washed out. The target protein is filtrated with technical water and spray-dried.

	Density [gcm^{-3}]	**Elastic Modulus [GPa]**	**Elongation [%]**	**Toughness [MJm^{-3}]**
Polyamide 66	1.1	5	18	80
Dragline *A. diadematus*	1.3	6	30	150

Table 1: Selected properties of polyamide 66 and natural spider silk ([12], [13])

1.2 Analysis of Environmental Impact

Life cycle assessment (LCA) models the whole life cycle of a product from cradle to grave and is conducted as specified in ISO norm 14040 and 14044 [14], [15], [16], where the four interrelated phases of an LCA have to be passed through as displayed in Figure 1.

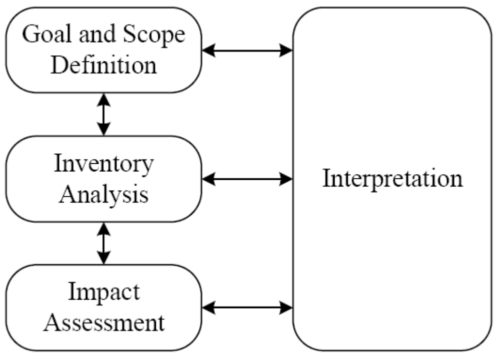

Figure 1: Phases of life cycle assessment (according to [14])

For comparative LCA, products with the same function or purpose are analyzed. Analysis is here accomplished with the life cycle assessment tool Umberto® by modeling material and energy input and output emission flows. In addition, the established life cycle inventory database ecoinvent was used for all generic datasets (ecoinvent v2.2). Ecoinvent provides consistent and transparent life cylce inventory data with more than 4,000 datasets.

2 INVENTORY ANALYSIS OF THE INVESTIGATED SYSTEM

For the comprehensive approach of an LCA, raw materials and energies used, and the resulting air emissions and water and soil discharges have to be summarized. This procedure is called *life cycle inventory analysis* and involves data collection and calculation of all relevant input and output flows of the examined product or production process [14]. Below the respective process steps are described.

2.1 Spider silk Production Process

By up-scaling the actual production process for spider silk, all material and energy flows are determined, and all relevant pre-processes are considered. For the raw materials deployed, either generic datasets of ecoinvent are used or, if no dataset of a raw material is available, the chemical synthesis is assumed using materials with existing datasets.

In Figure 2, main input and output flows of the spider silk production process are shown. The biotechnological process consumes different chemicals and glucose for cell growth and protein purification as well as utilities like electricity, heat and cooling energy, cleaning agents and others. For resulting waste, like biomass, sewage and exhaust air, post-processes have to be included in the modeling, to take into account their contribution to raw material consumption and caused emissions.

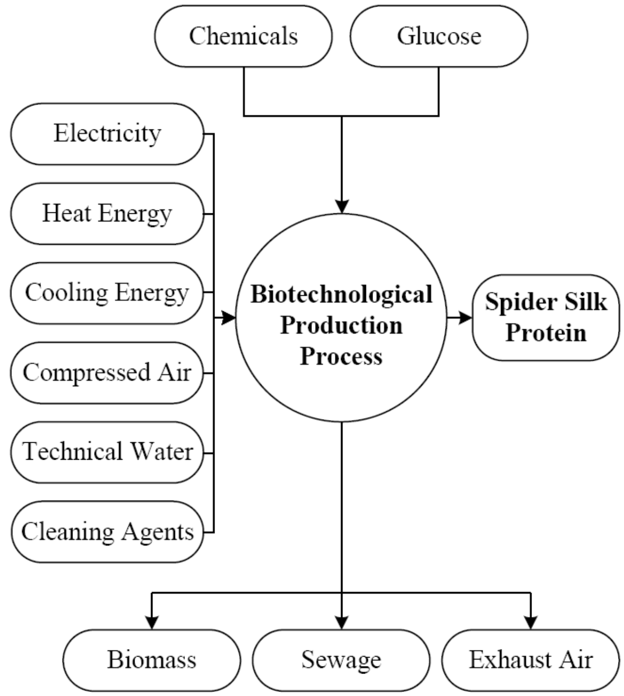

Figure 2: Input-Output-Scheme for the production process of spider silk

2.2 Polyamide 66 versus Spider Silk

The examined systems are shown in Figure 3. The production of spider silk is up-scaled based on laboratory data. For comparison, a generic module for the production of polyamide 66 is used. Polyamide 66 is synthesized from hexamethylenediamine and adipic acid [11]. In both cases the whole life cycle from cradle to grave of an airbag is considered. Here, the manufacture of raw materials, the production of the fiber material, the fabrication of the fiber, processing to a woven fabric, the assembly of the airbag and the recovery at the end of product life is taken into account. For comparative LCA, only differences in the production systems have to be included in the data collection.

The production of spider silk fibers and polyamide 66 fibers is different. Polyamide 66 fibers are melt-spun, and therefore a certain amount of energy is needed [11]. The spider silk fiber production is not applied in large-size, but based on the present laboratory process a production of the fibers out of aqueous solution is employed and up-scaled. The processing of the fibers to a woven fabric results in no input of resources and resulting emissions as further

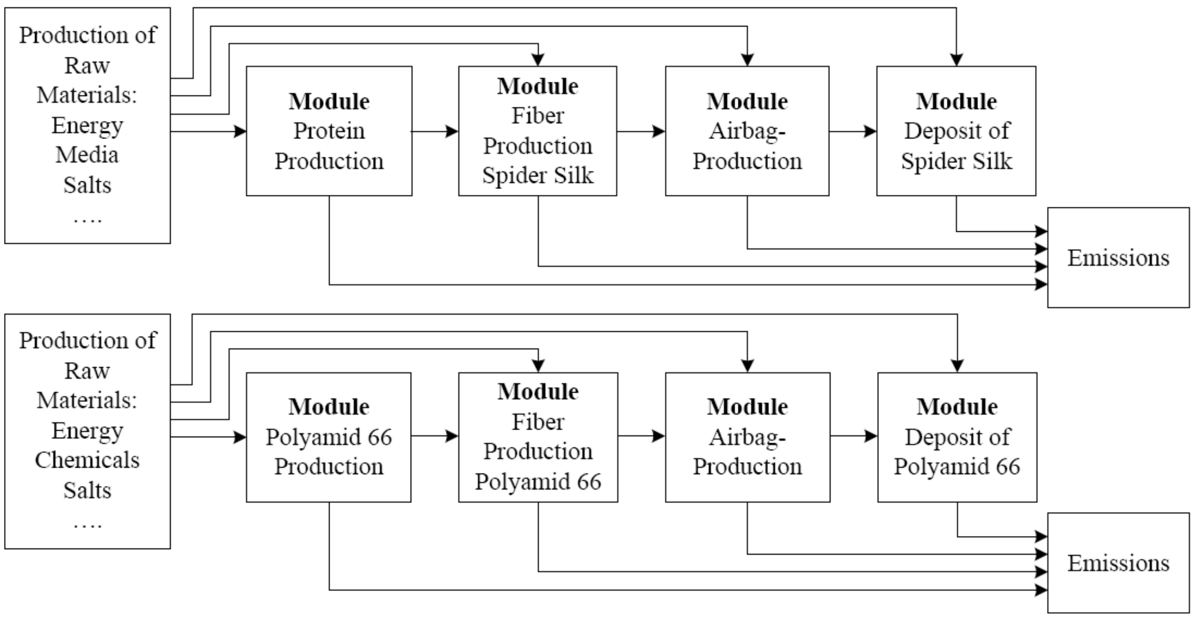

Figure 3: Basic flow diagram of spider silk production (top) and polyamide 66 production (bottom)

processing of both kinds of fibers is assumed to be the same.

For end-of-life of the polyamide fibers, an energetic recovery is typical, and the resulting amount of energy is allocated with the polyamide 66 production process [17], [18], [19]. Spider silk can easily be separated from other materials, therefore recycling can be assumed to a certain degree [20]. Necessary resources and resulting emissions of recycling of spider silk are modeled and allocated with the spider silk production process.

3 LIFE CYLCE IMPACT ASSESSMENT

For life cycle impact assessment (LCIA) the method of CML 2001 is used, developed by the Center of Environmental Sciences of Leiden University, the Netherlands [21]. For LCIA the resulting emission flows are assigned to impact factors and converted with equivalence units, for example kg CO_2 and subsequently summarized. The main impact categories and associated equivalence units are shown in Figure 4.

By adding up the equivalent units, the ecological impact can be compared for the two materials. Likewise, the raw materials used, can be analyzed for a product under development. Thus, it can be determined if use of another material is beneficial for future production. Also, main energy demanding process steps can be identified and thereupon optimized.

4 INTERPRETATION

In the interpretation phase of LCA the two product systems of airbag production are compared. Potential environmental effects can be indicated but it should be kept in mind that with the results of an LCA no actual prediction of impacts can be drawn. Though conclusions and recommendations for future decisions can be made, but they must always be related to the initial goal and scope of the conducted study.

Sensitivity analysis of critical process parameters and of decisions taken in course of LCA generation allows increasing reliability of emerging results. The interpretation phase can result in a change of decisions and in enhancing of data quality by more precise evaluation of data.

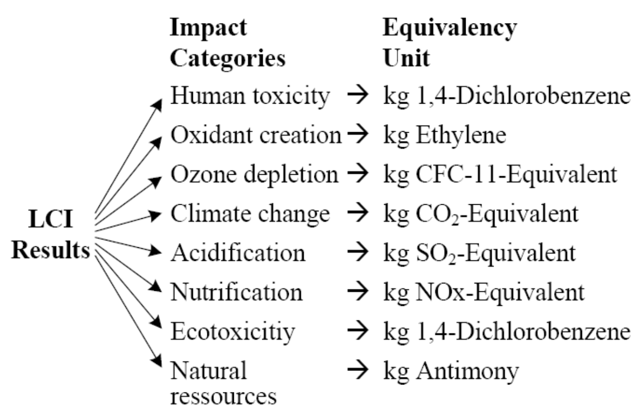

Figure 4: General structure of the LCIA framework (selection of categories, adopted from Jolliet et al. [22])

NSTI-Nanotech 2013, www.nsti.org, ISBN 978-1-4822-0586-2 Vol. 3, 2013

ACKNOWLEDGMENT

This research was supported by the Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz (AZ: U8793-2008/11-2 and U8793-2012/4-2)

REFERENCES

[1] T. Scheibel, "Spider silks: recombinant synthesis, assembly, spinning, and engineering of synthetic proteins," Microbial Cell Factories, 3:14, 2004.

[2] C. Vendrely, T. Scheibel, "Biotechnological production of spider-silk proteins enables new applications," Macromolecular Biosciences, 7, 401-409, 2007.

[3] D. Keerl & T. Scheibel, "Characterization of natural and biomimetic spider silk fibers," Bioinspired, Biomimetic and Nanobiomaterials, 1, 83-94, 2012.

[4] Vepari, D. L. Kaplan, "Silk as a biomaterial," Progress in Polymer Sciences, 32, 991-1007, 2007.

[5] G.H. Altman, F. Diaz, C. Jakuba, T. Calabro, R.L. Horan, J. Chen, H. Lu, J. Richmond, D.L. Kaplan, "Silk-based biomaterials," Biomaterials, 24(3), 401-416, 2003.

[6] D.Huemmerich, U. Slotta, T. Scheibel, "Processing and modification of films made from recombinant spider silk proteins," Applied Physics A, 82:2, 219-222, 2006.

[7] M. Humenik, A.M. Smith, T. Scheibel, "Recombinant spider silks – biopolymers with potential for future applications," Polymers, 3, 640-661, 2011.

[8] "The Application of Biotechnology to Industrial Sustainability," OECD Publishing, 2001.

[9] K. Hoppenheidt, W. Mücke, R. Peche, D. Tronecker, U. Roth, E. Würdinger, S. Hottenroth, W. Rommel, "Entlastungseffekte für die Umwelt durch Substitution konventioneller chemisch-technischer Prozesse und Produkte durch biotechnische Verfahren," UBA-Text 07/2005, Forschungsbericht 202 66 326, UBA-FB 000778, Umweltministerium des Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit.

[10] T.U. Gerngross, "Can biotechnology move us towards a sustainable society?," Nature Biotechnology, 17, 541-544, 1999.

[11] W. Burkhard, "Textile Fertigungsverfahren – Eine Einführung," Hanser Verlag München, 1998.

[12] F. Fourné; "Synthetic Fibers," Hansers Publishers Munich, 1998.

[13] A. Heidebrecht, T. Scheibel, "Recombinant production of spider silk proteins," Advances in Applied Microbiology, 82, 115-153, 2013.

[14] DIN EN ISO 14040: Environmental Management, Life Cycle Assessment, Principles and Framework, DIN (Deutsches Institut für Normung e.V.), Beuth Verlag, Berlin, Germany, 2006.

[15] DIN EN ISO 14044: Environmental Management, Life Cycle Assessment, Requirements and Guidelines, DIN (Deutsches Institut für Normung e. V.), Beuth Verlag, Berlin, Germany, 2006.

[16] W. Klöpfer, B. Grahl, "Ökobilanz (LCA)," Wiley Verlag Weinheim, 2009.

[17] R.S. Stein, "Polymer recycling: Opportunities and limitations," Proceedings of the National Academy of Sciences USA , 89, 835-838, 1992.

[18] J. Hopewell, R. Dvorak, E. Kosior, "Plastics recycling: challenges and opportunities," Philosophical Transactions of the Royal Society B, 364, 2115-2126, 2009.

[19] H. Geiger, H. Knopf, G. Leistner, R. Röme, H. Seifert, "Rohstoff-Recycling und Energie-gewinnung von Kunststoffabfällen," Chemie Ingenieur Technik, 65 (6), 703-709, 1993.

[20] Z. Zhu, Y. Kikuchi, K. Kojima, T. Tamura, N. Kuwabara, T. Nakamura, T. Asakura, "Mechanical properties of regenerated *Bombyx mori* silk fibers and recombinant silk fibers produced by transgenic silkworms," Journal of Biomaterials Science Polymer Edition., 21(3), 395-411, 2010.

[21] J.B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Wegener Sleeswijk, S. Suh, H.A. Udo de Haes, H. de Bruijn, R. van Duin, M.A.J. Huijbregts, "Handbook on life cycle assessment. Operational guide to the ISO standards," Kluwer Academic Publishers, 2002.

[22] O. Jolliet, A. Brent, M. Goedkoop, N. Stubo, R. Mueller-Wenk, C. Peña, R. Schenk, M. Stewart, B. Weidema, J. Bare, R. Heijungs, D. Pennignton, G. Rebitzer, N. Suppens, H.U. de Haes, "Final Report of the LCIA Definition Study," Life Cylce Impact Assesment Programm of the Life Cycle Initiative of the UNEP/SETAC Life Cycle Initiative, 12/2003.