A Brief Review: Synthetic Biology Applications in Sustainable Fashion

Belal Ansari and Abhilasha Gautam

Department of Biotechnology, Faculty of Engineering and Biotechnology, Rama University,Kanpur, Uttar Pradesh, India, 209217

Corresponding author:drabhilasha.fet@ramauniversity.ac.in

Abstract

Masses of resources, like water and energy, are used by the fashion industry, and thus the fashion industry is a key contributor to the degradation of natural resources. There are also a large number of waste produced and a very high level of pollution. This is why there is a growing demand for environmentally friendly fashions.Synthetic biology is an example of a way that scientists can use engineered living organisms such as fungi or bacteria to create environmentally friendly and useful products without using toxic chemicals and/or petroleum-based products in their production.Your research will help provide evidence that supports how synthetic biological processes can support the development of environmentally friendly fashions.The focus of this program will be on creating textiles made from natural fibres, such as animal hair, plant materials, and synthetic fibres; building up renewable and biodegradable sources of raw materials; dyeing products with non-toxic and low-impact chemicals such as vegetable dyes; and promoting recycling of textile materials by creating an efficient and effective way to recycle textile material after they have been used. In addition to discussing the benefits of utilizing these alternatives, the program will also address issues such as ethical and environmental concerns and current limitations of using these alternatives, along with the potential future difficulties associated with large scale production.

Keywords: Sustainable fashion, Synthetic biology, Biodegradable textiles, Renewable materials, Natural fibres, Eco-friendly dyes, Textile recycling, Circular economy, Environmental impact, Bioengineered materials

1.Introduction

The global fashion industry is known for the creative abilities and economic power of its businesses, but it is now being recognized globally as one of the most environmentally impactful industries in existence today. The process of producing textiles puts so much stress on the world's natural resources that it has been said that every stage of textile production creates a burden on our planet from the grower/producer of natural or man-made material through to the manufacturing process, the dyeing process, or the disposal of the finished product [1]. A single crop of cotton requires enormous amounts of water to grow, and the synthetic fibres (nylon, polyester, etc.), manufactured from petroleum products, create a substantial amount of carbon emissions during their

production and persist in the environment as microplastic fibres [2]. The emergence of fast fashion has further accelerated the speed at which manufacturers produce apparel, thereby resulting in tremendous amounts of textiles being consumed and even more occurring via discarded appear. As a result, there is a rapidly increasing necessity for a greater number of circular/sustainable forms of production within this sector.Because of this need, many areas of science- and particularly to what is being called 'synthetic biology' - are beginning to transform/redefine how materials are created/designed. Synthetic biology is an interdisciplinary field that combines aspects of biology, engineering and computational tools to enable the ability to program living organisms (such as microorganisms, including bacteria, yeast and fungi) to perform specific processes [3]. The modification of pathway genes in microorganisms allows for the ability to produce fibres, dyes and finishing agents, for example, in a consistent/controlled manner that can also be considered environmentally friendly. The use of synthetic biology in textile production significantly expands beyond just reducing environmental impact; it also fundamentally rethinks textile systems from an ecologically-sustainable perspective. Recent developments show that synthetic biology has many ways that it could change the future of fashion [4]. There are bio-fabricated materials, which include mycelium-derived leather substitutes and synthetic spider silk made with microbes [5], which can be used to replace resource-heavy or animal products. Also, new types of polymers made from bio-based raw materials, and cellulosic fibres produced from other bio-based materials, can replace petroleum-based materials, and they are often fully biodegradable and less damaging to the environment than synthetic options. Many research studies on new ways to use engineered enzymes and microbes to dye and finish textiles are being done to cut down on water, energy and chemicals used during these and other production processes [6]. This review compiles findings from several different studies to explore the impact of synthetic biology on creating a sustainable fashion system. By integrating research on bio-based materials, stimulating new product development, and innovating within clothing production processes within the limitations of current regulations, this review aims to outline the current state, new opportunities and challenges as synthetic biology continues to converge with design and help transform the fashion system into a circular low-environmental-impacted system of innovation and design[7].

Biological overviewed:

Synthetic biology is scientists using living organisms (including bacteria, fungi, and yeasts) as 'computers' to develop products that will be helpful[8]. The organisms being created are modified (the genetic code) so that they will function in specific roles and produce specific products (called 'cells programming').

2. Synthetic biology technologies are becoming important within fashion for several reasons: Bio-Based Textiles. The creation of bio-based textiles as opposed to petroleum-based textiles (e.g., polyester) will allow scientists to develop and produce fabrics from bio-based materials rather than oil, which could theoretically allow the creation of bio-textiles for a wide variety of uses.Microbial Dyeing, Scientists can create microorganisms through synthetic biology that will produce colours (dyes) for use on fabric that are safe and environmentally friendly [9]. The problem is that, because dyes produced using traditional methods require immense amounts of water and typically use toxic chemicals, dyeing fabrics using synthetic biology represents a more sustainable alternative to traditional processes.

sustainable-fashion-innovations-greener-future-sathish-kum

Biodegradable Materials. The fashion industry is creating biodegradable materials, providing the ability to reduce their environmental impact and promote a sustainable way to produce fashion products. Since bio-based materials can only last a relatively short duration (approximately six months to twelve months when composted), synthetically produced materials are essential to developing and distributing biodegradable materials for fashion.All of our materials in a circular production system shall be reused (the gap in your material flow will be closed), recycled (some of our materials will be re-extracted from previous locations), or returned safely to the environment (we will no longer use traditional "throw away" or use only once) if at least one of the three processes are available to us[10].

The primary processes in this section include:

Genetic Engineering

(Change the DNA of the organism)

⇓

Pathway Optimization

(Increase the amount of product created by an organism through increasing the efficiency with which the organism converts nothing to something)

⇓

Fermentation

(The use of microorganisms grown in a controlled environment to create a large amount of biomass)

3. Applications of Synthetic Biology in Sustainable Fashion

The use synthetic biology as a way to create sustainable fashion has been an important response to meeting the increasing need for environmental sustainability throughout the textile industry.The use of engineering techniques applied to organisms/living things can result in new types of environmentally sustainable fabrics from microorganisms (microbes) or synthetic biology. Below represents a small sample of synthetic biology's most impactful applications in the fashion industry [11].

3.1 Microbial Systems for Creating Textile Fabrication

An example of how microorganisms such as bacteria, yeast and fungi can be utilized to create ecoresponsible fashion is through bio-fabrication. Microbial systems provide access to the full range of available traditional textiles as they can be genetically modified to produce a wide range of fabric materials.The term "microbial cellulose" describes the type of cellulose produced by bacteria and is currently under investigation for its potential to replace traditional leather products. Silk-like fibres can also be produced using genetically modified yeast and/or bacteria rather than through the sericulture industry.In comparison to conventional manufacturing methods, bio-fabricated textiles are able to use less than 50% of the water used with conventional methods, produce less than 50% of the CO2 discharged as exhaust from conventional manufacturing operations, and utilise only plant-derived materials. As such, bio-fabrication is a far more sustainable (environmentally friendly) method of producing textiles than conventional textile manufacturing methods [12].

3.2 Microbial dyeing technology

Microorganisms can be engineered to produce natural pigments that may be used for dyeing fabric, thus giving rise to new options that are environmentally friendly and sustainable.For instance, certain bacteria generate natural pigments similar in colour to indigo dye and are normally used to create indigo blue denim; fungi, on the other hand, can produce an array of colours [13].These biological technologies present less of a reliance on hazardous chemical agents, reduce water pollution and energy consumption associated with the dyeing process, and thus represent a much cleaner and more sustainable means of dyeing than conventional dyeing processes.

3.3 Biodegradable and Bioengineered Material

The development of biodegradable and bioengineered materials is an additional significant use for synthetic biology. Biodegradable and bioengineered materials decompose naturally at the end of their useful life and will help to reduce the ongoing issue of textile waste.Protein-based fibres, bio-polymers and compostable textiles are some of these examples. Compared to traditional synthetic textiles which currently create microplastics, biodegradable textiles will decompose naturally in the environment.The use of biodegradable textiles as a way to reduce landfill volume and contamination to the environment make them a necessary part of the overall sustainable fashion system [14].

3.4 Circular fashion & Waste Minimization

Synthetic biology plays a vital role in promoting Circular Fashion and Waste Minimization. A circular fashion system seeks to reuse, recycle and regenerate materials through the reuse of these same materials.Using engineered microorganisms scientists can convert textile waste into new raw materials. Engineers can also create targeted microorganisms to decompose synthetic fibres for recycling at the molecular level.Doing so reduces our reliance on virgin resources and therefore also lessens our impact on the environment. Synthetic biology also supports Circular Economy principles to help create a more socially and environmentally sustainable and regenerative fashion industry [15].

4. Future prospects

4.1.Al - driven bio-design

Advancements in technology will provide many new opportunities for synthetic biology within the fashion industry, leading to significant changes in how textiles are made, used, and consumed. Environmental issues related to the fashion

industry and the need for more sustainable alternatives will continue to drive the development of synthetic biology solutions that can help address these challenges in the future. A newer and exciting aspect of interest in fashion is AI-based bio-design. AI bio-design utilizes both Artificial Intelligence and Biological Engineering to decrease the time required to create new garments using bio-based textiles materials. AI can also evaluate complex biological data and predict how well bioengineered textiles will perform according to their intended use (i.e., longer lifecycle vs shorter lifecycle, flexibility of performance characteristics or production process to meet sustainability) [16]. The combination of AI and Biological Engineering will significantly decrease the time to conduct experiments that support new designs for textiles; hence, designers will have greater accuracy and efficiency when developing new textile designs[17].

4.2.Scalable bio – Manufacturing

The next major change in developing scalable biomanufactured products is the ability to produce large quantities of bio-based products. Many bio-based products have been shown to work well in laboratories, but creating these materials on a large enough scale is problematic. Future R&D efforts will likely continue to develop detailed optimizations for fermentation and bioreactor systems, as well as to decrease costs of producing biofabricated textiles in order for them to be commercially successful and create global access within the fashion industry [18].

4.3. Smart and functional textiles

Moreover, synthetic biology is likely to lead to development of intelligent, functional textiles that can self-heal and respond to the environment, are antimicrobial, and have the ability to monitor a person's physical condition. These textile innovations will provide garments with additional functions beyond visual appearance. They will become multifunctional, creating opportunities for improved user experience while being sustainable [19].

4.4.Fully circular production system

The future will also introduce fully circular production systems, while the unsustainable model of production (where resources are "taken, made, and disposed") will be replaced by a sustainable circular economy model that recycles and regenerates resources endless times. One way to achieve this is through the use of engineered microbes to decompose the textile waste into its base materials so that those base materials can be recycled into new textile products [20]. This process can

greatly reduce the amount of waste created, conserve our planet's natural resources, and mitigate the environmental impacts related to producing textiles [21].

5.Interdisciplinary collaboration

Furthermore, to carry out the changes will require participation from numerous different sectors. Biotech companies, the fashion industry and researchers/policymakers will all need to collaborate across sector boundaries so that we can overcome the technical/economic/regulatory barriers that currently limit the development and use of bioengineered materials. The creation of standardised guidelines to facilitate innovation and to support the lawful and safe use of bioengineered materials will benefit all stakeholders engaged in the use of advanced technologies.

Conclusion

The world's fashion industry has made significant strides toward creating sustainable and innovative methods for clothing production. The industry has experienced an increased amount of change from the introduction of several new technologies into textile manufacture [22]. Manufacturers now have access to many different fibre types, which they can use to produce a wide range of fabric options, and not sacrifice environmental sustainability, or change the way consumers purchase clothing today. For example, clothing made from synthesized plant materials can be created that have similar characteristics to clothing made from organic cotton or wool [23]. Synthetic biology enables this to be done and will help textile manufacturers produce clothing that is "green" without sacrificing other important aspects of clothing to each consumer. Synthetic biology has also great potential to help resolve the major social and environmental issues currently facing the global textile industry [24]. For example, textiles made from synthesizing plant materials, such as corn and soybeans, will reduce the amount of land used and the water consumed in traditional forms of textiles.The fashion industry can benefit from biology in many ways.There are still many technical, safety and regulatory challenges that need to be solved. These challenges are stopping biology from being widely used.To make synthetic biology work on a scale we need to research and develop ways to produce bio-based products more cheaply. We also need to figure out the rules around bioengineered materials like how safe they're how to standardize them. This will help us move from small-scale tests to industrial use.Working together is key to solving the problems. There are more efforts to bring together scientists,

designers, industry people and policymakers. They are working on ideas and regulations. When people from fields work together sustainable practices will become more common in the fashion industry. Synthetic biology and sustainable practices will help the fashion industry.The fashion industry needs biology to make it more sustainable. Synthetic biology can help make materials. These materials can be used to make clothes. The clothes will be good for the environment.More people are working together. Scientists are working with designers. Industry people are working with policymakers. They are all trying to make the fashion industry more sustainable. They are using biology to do this.Synthetic biology is important. It can help the fashion industry. The industry needs to use biology. It will make the industry more sustainable. Sustainable practices are good for the environment. They are also good, for the industry.The industry will benefit from biology. It will help the environment. It will also help the industry. The industry needs to adopt practices. Synthetic biology will help the industry do this [25].

References

1. Uddin, F. *Introductory Chapter: Textile Manufacturing Processes*. *Textile Manufacturing Processes*, vol. 1, 2019, pp. 1–13.
2. Zhang, Z., et al. “Environmental Impacts of Cotton and Opportunities for Improvement.” *Nature Reviews Earth & Environment*, vol. 4, no. 10, 2023, pp. 703–715.
3. Benner, Steven A., and A. Michael Sismour. “Synthetic Biology.” *Nature Reviews Genetics*, vol. 6, no. 7, 2005, pp. 533–543.
4. Quijano, L., Richard Speight, and Alice Payne. “Future Fashion, Biotechnology and the Living World: Microbial Cell Factories and Forming New ‘Oddkins’.” *Continuum*, vol. 35, no. 6, 2021, pp. 897–913.
5. Kniep, J., et al. “Mycelium-Based Biomimetic Composite Structures as a Sustainable Leather Alternative.” *Materials Today Communications*, vol. 39, 2024, p. 109100.
6. Khan, M. F. “Recent Advances in Microbial Enzyme Applications for Sustainable Textile Processing and Waste Management.” *Sci*, vol. 7, no. 2, 2025, p. 46.
7. United Nations Environment Programme. *Sustainability and Circularity in the Textile Value Chain: Global Roadmap for Action*. UNEP, 2019.
8. World Wildlife Fund. *The Impact of Cotton on Freshwater Resources and Ecosystems*. WWF Report, 2013.
9. Jamee, R., and R. Siddique. “Biodegradation of Synthetic Dyes of Textile Effluent by Microorganisms: An Environmentally and Economically Sustainable Approach.” *European Journal of Microbiology and Immunology*, vol. 9, no. 4, 2019, pp. 114–118.
10. International Union for Conservation of Nature. *Primary Microplastics in the Oceans: A*

Global Evaluation of Sources. IUCN, 2017.

11. Ellen MacArthur Foundation. *A New Textiles Economy: Redesigning Fashion's Future*. Ellen MacArthur Foundation Publishing, 2017.
12. Cameron, D. E., C. J. Bashor, and J. J. Collins. "A Brief History of Synthetic Biology." *Nature Reviews Microbiology*, vol. 12, no. 5, 2014, pp. 381–390.
13. Youssef, Y. A., et al. "Indigo Dyeing and Antimicrobial Performance of Cotton/Bamboo Blend Denim Fabrics." *Research Journal of Textile and Apparel*, 2026, pp. 1–22.
14. Mehta, S. "Biodegradable Textile Polymers: A Review of Current Scenario and Future Opportunities." *Environmental Technology Reviews*, vol. 12, no. 1, 2023, pp. 441–457.
15. Yadav, P., M. Hakkarainen, and A. J. Varma. "Biopolymers and Biodegradable Materials for Sustainable Textile Applications." *Journal of Cleaner Production*, vol. 248, 2020, p. 119295.
16. Liu, Q., et al. "AI-and Biotechnology-Driven Digital Design of Biohydrogen-Producing Microbiota." *Engineering*, 2025.
17. McKinsey & Company. *The State of Fashion Technology: AI and Bio-Design Innovations*. McKinsey Insights, 2023.
18. Rognoli, V., et al. "Materials Biography as a Tool for Designers' Exploration of Bio-Based and Bio-Fabricated Materials for the Sustainable Fashion Industry." *Sustainability: Science, Practice and Policy*, vol. 18, no. 1, 2022, pp. 749–772.
19. Adak, B., and S. Mukhopadhyay, editors. *Smart and Functional Textiles*. Walter de Gruyter GmbH & Co KG, 2023.
20. Leitenberger, F., et al. "Towards Perpetual Innovative Products Through Circular Factories: Integration of Functional Behavior into System Reliability." *Procedia CIRP*, vol. 136, 2025, pp. 426–431.
21. Organisation for Economic Co-operation and Development. *Scaling up the Bioeconomy: Strategies for Sustainable Industrial Biotechnology*. OECD Publishing, 2021.
22. Fromhold-Eisebith, M., et al. "Torn between Digitized Future and Context Dependent Past–How Implementing 'Industry 4.0' Production Technologies Could Transform the German Textile Industry." *Technological Forecasting and Social Change*, vol. 166, 2021, p. 120620.
23. Dhange, V. K., S. M. Landage, and G. M. Moog. "Organic Cotton: Fibre to Fashion." *Sustainable Approaches in Textiles and Fashion: Fibres, Raw Materials and Product Development*, Springer Nature Singapore, 2022, pp. 275–306.
24. Kiran, B. R., M. N. V. Prasad, and S. V. Mohan. "Synthetic Biology: An Emerging Field for Developing Economies." *Bioremediation and Bioeconomy*, Elsevier, 2024, pp. 767–787.
25. Robinson, D. K., and D. Nadal. *Synthetic Biology in Focus*. OECD Science, Technology and Industry Working Papers, 2025.