Scientific and Social Research, 2026, Volume 8, Issue 1
https://ojs.bbwpublisher.com/index.php/SSR
Online ISSN: 2981-9946
Print ISSN: 2661-4332

# Synthetic Biology Empowers Cosmetics to Enter a New Era of Biomanufacturing

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**Abstract:** With the rapid development of synthetic biology technology, the cosmetics industry has entered an unprecedented technological revolution. Against this background, this paper conducts research from two aspects: on the one hand, by analyzing the popular application of synthetic biology technologies such as gene editing, microbial fermentation, and enzyme engineering, the paper summarizes the breakthrough progress of the cosmetics industry in recombinant humanized collagen, natural plant functional ingredients, and new emulsification and stabilization systems; on the other hand, by elaborating on the advantages of synthetic biology in safety, efficacy, and sustainability in cosmetic production and manufacturing, the paper further looks forward to the future mature application and multi-disciplinary integrated development path. The aim is to promote the cosmetics industry to accelerate towards personalization, precision, and sustainable development, and truly usher in a new era of biomanufacturing.

**Keywords:** Synthetic biology; Biomanufacturing; Cosmetic raw materials; Recombinant collagen; Cell factory; Green manufacturing

**Online publication:** January 30, 2026

## 1. Introduction

With the development of the times and the continuous improvement of people's living standards, cosmetics have become one of the common consumer goods in human daily life. Their production and manufacturing have undergone an evolutionary path from extraction from natural animals and plants to chemical synthesis, and now to biomanufacturing, forming a complete and standardized production and manufacturing process. Traditional cosmetic raw material production methods have drawbacks such as strong resource dependence, high safety risks, and serious environmental pollution. Synthetic biology technology provides a solution: by designing and modifying biological systems and creating cell factories, it realizes efficient and green manufacturing of target products, providing unprecedented technical support for the transformation and upgrading of the cosmetics industry.

## 2. Analysis of new cosmetic functional ingredients in the field of synthetic biology

### 2.1. Recombinant humanized collagen: from structural bionics to functional transcendence

Collagen is one of the important components of the extracellular matrix of human skin cells, so it has long been a core functional ingredient of concern in the cosmetics field. Traditional collagen production methods from animal sources face risks such as viral contamination, functional limitations, and immunogenicity. Through genetic recombination and microbial fermentation technology, synthetic biology has achieved the safe and large-scale production of recombinant humanized collagen, fundamentally solving the production and application dilemmas of collagen [1].

In terms of technological development, the biosynthetic process of collagen is continuously upgrading. For example, Jinbo Biology has innovatively developed WeaveCOL collagen based on synthetic biology technology. It adopts a precise conformation of a 164.88° triple helix structure, thus achieving a high degree of consistency with human collagen, improving the repair effect of collagen's "structure repairing structure", and greatly enhancing its biological activity and compatibility, showing more prominent application effects in the cosmetics field [2].

In terms of industrial construction, recombinant collagen has achieved a leap from laboratory to large-scale production, and clarified the five-link production process of "gene design and optimization, gene synthesis and vector construction, protein expression, protein purification, and functional verification and quality control" [3]. It not only completely avoids potential risks from animal sources but also meets the manufacturing standards of environmental protection, controllability, and precision.

### 2.2. Natural herbal plant ingredients: From resource dependence to sustainable manufacturing

Traditional herbal plant resources have always had important advantages in the field of cosmetic manufacturing. However, plant extraction methods not only affect the ecological environment but are also affected by factors such as resource limitations, unstable ingredients, and low extraction efficiency. Synthetic biology has realized the biosynthesis of various rare active plant ingredients by constructing microbial cell factories, thus achieving an upgrade from resource dependence to sustainable manufacturing.

For example, natural plant-derived cosmetic ingredients such as terpenoid fragrances, ergothioneine, royal jelly acid, and *Lamiophlomis rotata* extracts traditionally need to be extracted from natural resources such as plants, fungi, and royal jelly [4]. Under the biosynthetic pathway, they can be continuously obtained through yeast cell factories, *Escherichia coli*/yeast engineering bacteria, genetically engineered bacteria, and plant cell culture. Taking terpenoid fragrances as an example, yeast cell factories can now achieve precise manufacturing of various terpenoid fragrances [5]. Such ingredients not only provide a good sensory experience but also have multiple physiological functions. For instance, β-caryophyllene can produce a woody spicy fragrance, has antibacterial and anti-inflammatory effects, and can be more efficiently absorbed by the skin [6].

### 2.3. Emulsification and stabilization systems: From chemical stabilization to biocompatibility

In cosmetic manufacturing, in addition to key ingredients that produce core skincare effects, ingredients such as emulsifiers, stabilizers, surfactants, and preservatives are also needed to ensure that cosmetics remain stable during storage and use, and achieve the effects and purposes of ease of use and rapid absorption. Therefore, emulsification and stabilization systems have become important factors affecting the stability and user experience of cosmetics. Most chemical emulsifiers used in traditional cosmetic production cause certain irritation, and their production

processes also increase environmental burden. Synthetic biology technology provides a green and safe alternative.

In terms of the research and development of stabilization system technology, the team of Jiang Lingxiang from South China University of Technology synthesized a new type of block polymer that can universally stabilize various "condensed phase-water phase" interfaces. Such molecules can protect and maintain the "condensed phase-water phase" interface by spontaneously forming a film layer, thereby improving the stability and tolerance of droplets [7]. This technology will play a significant role in the field of cosmetic manufacturing.

In terms of the research and development of emulsification system technology, a team from a Republic of Korean university used ultrasound to break microalgae and used their cell debris as emulsifiers, which showed excellent emulsifying and thickening properties in oil-in-water emulsions. At the same time, by regulating ultrasonic energy, more surface-active proteins can be better released from microalgae cells, thereby establishing a "cellulose-protein composite network", which can reduce droplet size and increase viscosity, providing a new idea for the development of "green" emulsions without synthetic surfactants [8].

## 3. Advantages of synthetic biology in modern cosmetic production and manufacturing

### 3.1. Realizing green and sustainable manufacturing

Synthetic biology technology has essentially changed the traditional production and manufacturing processes of cosmetic raw materials, and gradually separated from the dependence on fossil resources and extraction from animals and plants, moving towards a green and sustainable manufacturing industry. In terms of resource utilization, glucose, corn, and other resources have become important raw materials for microbial fermentation processes, and reactions and synthesis are realized under normal temperature and pressure, with significant advantages of low energy consumption and low pollution. In terms of environmental impact, traditional cosmetic raw material production involves animal slaughter, plant collection, and consumes a large amount of water, chemicals, and chemical energy, resulting in significant environmental pollution and negative impacts. However, synthetic biology technology can effectively avoid most of these problems, reducing energy consumption by 15%–30%, carbon emissions by 20%–35%, and wastewater discharge by more than 50% [9]. In addition, synthetic biology can also provide a new approach for the protection and sustainable utilization of rare biological resources. For example, "giant salamander glycopeptides" can be isolated from the skin mucus of protected giant salamanders through bioenzymatic hydrolysis and refined extraction technology. This core active ingredient has important value in the field of cosmetic research and development [10]. At the same time, this production model can better promote animal protection and biodiversity development, achieving a win-win situation between ecological protection and industrial development.

### 3.2. Leapfrog improvement in product quality and safety

Synthetic biology has not only innovated the growth process of cosmetic raw materials but also fundamentally improved the quality and safety of cosmetics. First, through humanized ingredient design, it reduces rejection risks, improves the biocompatibility of cosmetic ingredients, and meets safety requirements at all levels, from raw material sources, structural characteristics, to functional realization. For example, in collagen production, the precise conformation of biosynthetic technology can not only solve the potential immunogenicity problems of traditional animal-derived collagen but also improve collagen activity and form an efficient communication mechanism with human cells, thereby achieving the effect of improving product repair functions [11]. Second, the

precise structure ensures the consistency and stability of efficacy. Cosmetic production under synthetic biology technology can accurately control the molecular structure of products, thus ensuring that products of different batches have the same quality level. Third, it realizes raw material purification and forms safety guarantees. Synthetic biology can rely on closed fermentation systems and other process methods to fundamentally cut off risk factors such as allergens and pathogens that may be carried by animal and plant raw materials.

### 3.3. Significant enhancement of production economy and flexibility

Synthetic biology technology can significantly improve the production efficiency of cosmetic raw materials and show higher flexibility, thereby achieving the purpose of improving economic benefits and market response capabilities. First, it has advantages in production efficiency and cost. With the support of metabolic pathways in microbial cell factories, synthetic biology technology can greatly increase the production speed of cosmetics, achieve magnitude breakthroughs in the output efficiency of some ingredients, and significantly reduce costs, which is conducive to the further popularization and promotion of original high-end cosmetic raw materials [12]. Second, production is more flexible and can meet customized needs. Synthetic biology platforms can quickly switch product production content to respond to market demands in a timely manner. For example, at this stage, the same strain of yeast can be promoted to synthesize multiple ingredients simultaneously through efficient metabolic transformation technology, achieving the effect of "one bacterium with multiple functions" [13]. Third, the innovation cycle is significantly shortened. Especially with the support of standardized biological parts and efficient gene editing tools, the speed of cosmetic research and development is rapidly increasing, and new products can be continuously launched.

## 4. Future outlook of synthetic biology empowering the development of the cosmetics industry

### 4.1. Technology innovation and industrial upgrading paths

The application and innovation of synthetic biology technology in the field of cosmetic production are on the ascendant, and it will continue to provide motivation in multiple dimensions to promote the upgrading of the cosmetics industry in the future. At the same time, with the continuous upgrading and popularization of gene editing technology, artificial intelligence, and high-throughput screening platforms, the biomanufacturing model of cosmetic raw materials will have a more precise and efficient development prospect.

From a technical perspective, multi-disciplinary cross-integration will become the core driving force for the further development and application of synthetic biology technology. From an industrial construction perspective, introducing relevant technologies from the laboratory to the factory is a key link that needs to be focused on to break through. The key to technology transformation lies in production costs, process feasibility, and market competitiveness. Therefore, the future technological innovation of synthetic biology in the cosmetics field will roughly develop in the following three aspects: first, the construction of high-efficiency chassis cells, aiming to develop universal chassis with strong adaptability and high yield [14]; second, the optimization and innovation of bioreactors, focusing on giving play to the advantages of digital technology; third, the innovation of downstream separation and purification technology, focusing on reducing purification costs and improving product recovery rate with the help of new separation materials and processes.

### 4.2. Industry ecology and value reconstruction

Synthetic biology technology provides a new cosmetic manufacturing model and reshapes the industrial chain, value chain, and development ecology of the cosmetics industry. Looking forward to the future, the application of synthetic biology in the cosmetics field will promote the transformation of the cosmetics industry from marketing-driven to technology-driven. It is necessary to highlight the value of technology and transform from "technology follower" to "standard setter" to demonstrate the core competitiveness of enterprises. From an individual perspective, synthetic biology will also help the cosmetics industry develop towards a new paradigm of personalized skincare. Especially with the support of cutting-edge sciences such as skin genomics and microbiomics, customized active ingredients and cosmetics can be provided according to the specific needs of different groups and individuals [15].

### 4.3. Global development and standard leadership

Synthetic biology technology also provides a shortcut for China's cosmetic manufacturing enterprises to "overtake on curves." On the one hand, synthetic biology technology has broken through the traditional routes and processes of cosmetic research and development, fundamentally bringing new opportunities for the global development of Chinese enterprises. Especially with the support of massive technological innovations, excellent Chinese cosmetic enterprises have gained unique competitiveness in the global market. On the other hand, with the in-depth application of synthetic biology in the cosmetics field, the construction of technical standard systems and regulatory frameworks has begun, which is not only a key route for the evolution of internal enterprise standards to industry standards but also an important channel to regulate market order and promote the healthy development of the industry.

## 5. Conclusion

In summary, synthetic biology is driving the cosmetics industry towards the era of biomanufacturing, and has reconstructed and improved it from the aspects of technology, industrial model, value concept, and industry structure. With the support of synthetic biology, modern cosmetic production models are safer, more efficient, and sustainable, and can effectively improve the economy and environmental friendliness of industrial production. It can even promote China's cosmetics industry to move towards the world stage, gradually leaping from the "follower" stage to the "leader" stage, and realizing greater development aspirations.

## Disclosure statement

The authors declare no conflict of interest.

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