

The Application and Performance Advantages of Synthetic Biology in Cosmetics Ingredient Production

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Abstract. As an emerging interdisciplinary field, synthetic biology is having a profound impact on the cosmetics industry. This study aims to systematically explore the applications and effects of this approach in the production of cosmetic active ingredients. Genetic engineering and the reconstruction of microbial cell factories enable the efficient and sustainable production of natural active compounds with high purity and stability. Besides, synthetic biology strategies enable the sustainable and scalable production of natural colourants and their non-natural derivatives, offering green and innovative solutions for the cosmetics and personal-care industries. This essay begins by presenting the definition and general principles of synthetic biology. Next, it examines its current applications and performance advantages within the cosmetics sector. Finally, it considers the challenges brought by existing approaches. The final goal is to create practical references and insights for the innovative construction of the industry.

Keywords: Synthetic Biology, Cosmetics Industry, Microbial Fermentation, Sustainable Production, Bio-based Ingredient.

1. Introduction

Cosmetics are extremely important in our days. 'Vitamin C morning and retinol evening', 'exfoliation with acids' and 'oil skincare' are modern trends on social networks among Generation Z consumers. Skincare ingredients research for Generation Z consumers goes far beyond the basic needs of hydration and moisturising and tends more towards advanced needs such as 'precise anti-ageing' and 'microbiome balance'. Due to rising living standards and changing behaviour of consumers, cosmetics business is on the rise. Consumers today no longer think of cosmetics as something simple to clean their faces and make them appear beautiful; now consumers care about the performance, safety and sustainability of cosmetics. Cosmetic ingredients till date have been either naturally extracted or chemically synthesised. Both have their cons. Chemical synthesis is environmentally unsafe and may cause irritation to skin with certain compounds. The cons of naturally extracted ingredients include low availability of the material, variation between batches and possible ecological toxicity. According to CBND ata, consumers are already familiar with the phrase 'bio-based ingredients' and the majority of them are willing to pay a premium of 45% for green certified products [1].

In this scenario, synthetic biology comes as an enabler to develop new cosmetics. Using an engineering-driven paradigm framed as 'Design–Build–Test–Learn' (DBTL), synthetic biology makes sustainable production possible in new ways. Through rational design and engineering of microbial cell factory, synthetic biology offers highly efficient, controlled and environment-friendly solutions for bulk production of cosmetic active ingredients [2].

2. Definition and Principles of Synthetic Biology

Synthetic biology is a highly innovative and interdisciplinary science, which has been called the 'third biotechnology revolution' [3]. In essence, it is the use of engineering tools to build new biological systems from scratch. One might say that it is the 'LEGO of the world of biology', as biologists can now take genetic parts and put them together in a controlled way, much like a child would build a tower with LEGO bricks. By combining technology such as gene editing, metabolic

engineering and systems biology, synthetic biology can modify a microorganism, plant cell or animal cell, which can then be endowed with a particular function, making them extremely efficient ‘cell factories’ that can produce a target molecule upon demand [4]. These functions can contribute to the new design of advanced biomaterials and bio-based products for different industries. [5].

2.1. Classification

Synthetic biology can be divided into three categories: microbial, plant and animal. Due to their characteristics, microbial synthetic biology has garnered more attention in cosmetics manufacturing because microorganisms reproduce very rapidly. Under ideal conditions, some bacteria can duplicate every 20 minutes, so their biomass can increase exponentially in a short time and provide an ideal basis for the large-scale biosynthesis of active components [6]. They have low requirements for nutrition and the environment and can be content with simple culture media, which lowers costs and makes the process easier and more efficient. In addition to these advantages, microbial systems also provide solid support for sustainability. Fermentation uses renewable feedstocks such as sugars, crop residues or other bio-based streams, so dependence on finite natural resources is minimized and the environmental damage caused by over-harvesting is removed. Moreover, the fermentation process is less contaminating and safer than traditional chemical synthesis because it generates fewer by-products and is easier to treat waste streams, so the environment is less impacted [7]. For these reasons, microbial synthetic biology enables the accurate and controlled production of cosmetics actives such as hyaluronic acid and antioxidants with stable quality and an environmentally friendly process.

Multi-enzyme systems and recombinant microbial cells have been successfully engineered to synthesize valuable saccharides such as hyaluronic acid with dramatically improved yield and greatly reduced environmental footprint [7].

2.2. Principle

The essence of synthetic biology is the accurate and reliable design and control of genes, metabolic pathways and entire cell systems. The discovery of highly effective gene-editing tools, notably the CRISPR–Cas9 system, have provided researchers with extremely potent tools. They can make very accurate genetic changes, such as deleting a specific gene or inserting one, and make edits and therefore change the cells’ genetic material with previously unimaginable efficiency and precision. These therapies make up part of the arsenal of biological research tools and hold huge potential for industrial applications [8].

Metabolic engineering is another key component of synthetic biology. It’s the optimization and redesigning of intracellular metabolic process to direct the cellular resources into efficient production of target molecules. This can be achieved by introducing new genes, regulating the expression levels of endogenous genes, and redirecting the metabolic fluxes. These help scientists to construct new biosynthetic pathways so that cells can produce important bioactive compounds in a predicted and controlled way [9]. Furthermore, synthetic biology is not limited to individual genes or pathways but also involves the design of complex gene regulatory networks that can deliver spatiotemporal precision in regulating the growth and product biosynthesis of microbes, thus improving the production efficiency as well as end-product quality at the same time. Finally, these technologies are applied in building ‘cell factories’ where enzymes, transport proteins and other functional modules are rationally integrated into a single microbial chassis to achieve maximal biosynthetic yield. For instance, Bloomage Biotech successfully engineered *Streptococcus* to make hyaluronic acid through eliminating interfering genes, optimizing the biosynthetic pathway and using a two-stage temperature control system. By eliminating competing pathways and optimizing a two-stage temperature-shift strategy, engineered *Streptococcus* raised HA titers from 72 g L⁻¹ to 108 g L⁻¹ and shortened the production cycle [7].

Bluepha also succeeded in introducing an ergothioneine biosynthesis module into *Escherichia coli*. A one-step microbial conversion of glucose to high-purity ergothioneine was achieved by rewiring central carbon metabolism and introducing a heterologous biosynthetic module into *E. coli*.

These applications reveal the revolutionary potential for synthetic biology in cosmetics manufacturing. By designing and implementing strategies ranging from the molecular level to the whole cell system, synthetic biology offers scope for higher yield and better-quality active ingredients as well as improved sustainability in raw material production. This new approach brings about transformational answers to the cosmetics industry, unlocking the path to scalable, sustainable and environment-friendly biomanufacturing processes [10].

3. Current Applications of Synthetic Biology to Cosmetics

3.1. The Production of Hyaluronic Acid

In cosmetics, besides water, hyaluronic acid (HA) is generally acknowledged as one of the most popular, most efficient and most dominant moisturising materials all over the world. With the development of synthetic biology and the optimization of the whole process of bioprocessing, HA can also be produced via microbial fermentation as an economical and sustainable alternative to animal extraction.

However, HA has also been produced primarily by extracting it from animal tissues such as rooster combs. There are also some disadvantages of this method: the yield is low and can never keep pace with the constantly increasing demand of the market, the extraction process is complicated and expensive, the quality of the product is sometimes unstable, and the fact that it is derived from animals is capable of causing allergic reactions, animal-derived impurities and other ethical problems as well as the risk of disease transmission.

With the development of synthetic biology, which opens a new page for the production of HA beyond the limitations of traditional technology, microbial fermentation has become the key approach. Researchers have used genetic engineering technology to control microorganisms as ideal hosts to produce hyaluronic acid. By introducing the relevant genes and optimising the metabolic process and culture conditions, the desired microorganisms can be induced to produce stable and efficient amounts of hyaluronic acid on an industrial scale. This process has many advantages: it can greatly increase the yield to meet the bulk demand of the cosmetic industry; it can produce higher-purity and more stable HA; it can remove impurities and contaminants from animal-derived products; it can also remove impurities and contaminants from animal-derived products; it can reduce the cost of production, making HA more affordable; and it can also remove animal testing, solve ethical issues and reduce the possibility of disease transmission, thus realizing the sustainable development of cosmetic [11].

3.2. Synthesis of Squalenes

Squalane is a different cosmetic active ingredient used in a vast array of cosmetics with similar moisturising, nourishing and antioxidant properties. The original source of squalane has been shark liver. This activity damaged marine ecosystems and led to significant issues with sustainability and scalability. It was expensive to extract as huge amounts of shark liver were required to produce tiny amounts of squalane, and it had a moral component as it led to the over-exploitation and destruction of sharks.

Researchers have facilitated the use of high-tech screening to identify microbial strains that naturally produce squalane or genetically modify the strain to increase its capacity to produce squalane. These sophisticated engineered microbial cell factories use renewable feedstocks like glucose or glycerol and produce squalane from them through a series of biochemical reactions during fermentation [12].

This results in a clean and environmentally friendly process that significantly decreases the environmental impact compared to traditional processes. It is free from the use of harmful chemical solvents and reduces waste streams with additional advantages of enhanced control of final product purity and quality. The renewable feedstocks provide a stable and scalable supply of squalane to meet the increasing demand from cosmetics without impacting environmental sustainability or animal

welfare [12]. Furthermore, squalane produced from synthetic biology does not contain contaminants and impurities found in shark liver-sourced squalane, hence it is safe and effective to use in skincare products [12].

3.3. Other Active Ingredient Production

In addition, squalane from synthetic biology is not contaminated with impurities as shark liver squalane is, so it is very safe and can be used in skincare products.

In addition to hyaluronic acid and squalane, there are many other active ingredients that have been successfully synthesised using synthetic biology, such as collagen, ceramides and vitamins.

Genetically modified microbial cells can express and secrete collagen fragments with known amino acid sequences and three-dimensional structure, producing highly bioactive and defined target proteins as well as highly effective and well-defined functional ingredients for cosmetics such as anti-ageing products.

Metabolic engineering was used to design the biosynthetic pathway of ceramides, which can well mimic the molecular structure of natural ceramides in the stratum corneum of human skin, thereby repairing the skin barrier and alleviating skin dryness and sensitivity.

In addition, microorganisms can synthesise water- and fat-soluble vitamin C (ascorbic acid) and vitamin E (tocopherol), which can enhance the purity and bioavailability of products and endow cosmetics with healthy, antioxidant-active ingredients.

Microbial biosynthesis of sesquiterpenols, including bisabolol and patchoulol, has been achieved with titers above 5g/L⁻¹. Cosmetics formulators can use this to obtain fragrances and anti-inflammatories derived from natural materials [13].

4. Performance Benefits of Synthetic Biology in Cosmetics

4.1. Ingredient Purity and Performance Improvement

Along with other emerging technologies in biomanufacturing, microbial fermentation technology has the magical power to guide active molecule synthesis to any desired direction. By controlling the conditions of reactions and microbial metabolic networks, microbial fermentation not only yields high purity products, but also greatly reduces or even eliminates impurities that are usually present in extracted materials, resulting in much higher quality and stability of the products.

In contrast, traditional β -glucan production involves physical or chemical extraction from its original materials. The original materials are usually of relatively low purity and may contain various impurities such as polysaccharides, proteins and unidentified substances, which affect stability, lower efficacy and induce allergic reactions. However, genetically modified yeast can be engineered to produce the key enzymes needed for β -glucan formation to yield specific, high-level pure β -glucan. By finely controlling the conditions of fermentation, including temperature, pH, dissolved oxygen and nutrient content, β -glucan purity can be raised to over 99% [14], impurities can be eliminated greatly and safety can be greatly improved.

Due to its unique molecular structure and physicochemical properties, high-purity β -glucan also has enhanced moisturising and soothing properties. High-purity β -glucan swells and generates a thick and even moisturising film on the skin, attracting and maintaining moisture in the skin and preventing water loss. At the same time, high-purity β -glucan controls the intensity of the immune response to minimise irritation. This makes high-purity β -glucan well suited to meet the high requirements for cosmetic ingredients.

4.2. Targeted Optimisation of Functional Molecules

Gene fine-tuning technology is a highly intelligent and specific new technology for modifying the molecules produced by microbes. It can optimise certain functions of microbes greatly and can be applied in many other fields. For example, when hyaluronic acid is synthesised, we can fine-tune the genes encoding hyaluronic acid synthase intelligently and specifically to tightly control the metabolic

functions of the microbes and to synthesise hyaluronic acids with various molecular weights. The high-molecular-weight hyaluronic acid can serve as a good film former and can be easily spread onto the skin to form a highly stratum-ooching and highly compact hydrating film on the skin surface [15]. This can prevent water loss and keep the skin in a hydrated state. In contrast, low-molecular-weight hyaluronic acid can penetrate better and reach the deep layers of the skin very quickly. There it gets in contact with skin cells to give the skin excellent repair and moisturising properties, promotes skin metabolism and gives the skin more elasticity and more radiance.

This fine-tuning strategy to produce cosmetics in an exact optimal way for different types of skin and individualised needs makes it possible to produce skincare products ideally suited to the needs of each consumer in search of beauty and well-being.

4.3. Identification of Potential New Molecules

Compared with biological limitations, synthetic biology avoids these restrictions and provides an unlimited range for discovering and synthesising new active molecules. Researchers design new enzymes or metabolic pathways to synthesise new compounds with desired functions and characteristics. These compounds are antioxidants, anti-inflammatory agents or skin-lightening agents. Peptide growth factors are of great importance in skin repair and anti-ageing. However, the peptide growth factors obtained by chemical synthesis have low activity and stability. In contrast, if we use synthetic biology to genetically and metabolically engineer microorganisms to synthesise such peptide growth factors, the results would be greatly successful.

"Microbially expressed analogues of human TGF- β -mimetic peptides retained $\approx$ 60% higher antioxidant and cell-proliferation activity after 72h at 37°C than their chemically synthesised counterparts, anti-ageing products, and infusing new life into the cosmetic industry [16].

4.4. Case Study Analysis

4.4.1 Ceramide Case Study

Ceramides have been conventionally obtained from animals and plants such as rice bran, wheat germ and brain tissue. As seen, it has several demerits. First of all, the raw materials are limited to certain areas and even seasons depending on the material, such as rice bran, wheat germ and brain tissue. It is impossible to find a constant and sufficient material source because the quantity is variable depending on the seasons and the scale of culture. It leads to fluctuating and small amounts of yield according to the market demand. Second, the extraction process is very tedious and expensive. It consists of many steps of purification and separation, and uses large amounts of organic solvents. It leads to increased cost and environmental pollution. Lastly, ceramides extracted from the above methods have low purity and impurities are included in them. They may be useless in cosmetic products because impurities may hinder the effect of cosmetic products or even cause skin allergies.

However, ceramides can be produced stably at a reasonable price with the development of biotechnology. Screening and designing specific microbial strains and controlling the fermentation conditions, such as temperature, pH, dissolved oxygen and the supply of nutrients, ceramides can be produced at economic prices. Compared to conventional extraction methods, the cost of ceramides produced by microbial fermentation is reduced by about 35%.

In addition, controlled fermentation conditions can ensure high purity and consistent quality of products (over 98% [17]). High-purity ceramides are easily absorbed by the skin and have good effects on skin barrier repair, moisturising and caring. Therefore, they have become the favourite of high-end cosmetic products for cosmetic ingredients because customers have higher requirements for cosmetic ingredients.

4.4.2 Coenzyme Q10 Case Study

In beauty care, coenzyme Q10 has drawn great attention due to its high antioxidant activity. It can sweep out the free radicals inside skin cells effectively, and stop the ageing process of skin cells.

The obtained Fermentation CoQ10 is all-trans natural configuration, and the anti-oxidation activity of it is over 60% more than the chemically synthesised quasimolecules [18]. Though we can produce coenzyme Q10 in large amounts by chemical synthesis, there are also obvious disadvantages in the process. There are toxic reagents used in the process, and certainly, they will be in the product and will damage our health. Besides, the coenzyme Q10 obtained by chemical synthesis does not definite stereochemistry, so there are many isomers generated, and some isomers may have biological activities which decrease the effectiveness of the product.

In the last decade or so, microbial fermentation has become a promising approach to producing CoQ10. Using a specific microorganism, such as rhizobia in optimum growth media to ferment can enable the microbe to synthesise CoQ10 from the feed nutrient. The CoQ10 obtained by fermentation is maintained in a natural stereostructure and practically all the isomers are bioactive, leading to a very high content of effective components. Compared with chemical synthesis, the quality and safety of fermented CoQ10 are better. Furthermore, with the continuous optimisation and purification in the fermentation process, the cost of the fermentation process has been decreased step by step, and now it can be compared with or even cheaper than chemical synthesis. Therefore, fermentation-produced CoQ10 has been widely used in the cosmetic industry to produce safe and highly potent anti-ageing products.

5. Challenges of Existing Approaches

5.1. Technical Challenges

Despite the significant achievements of synthetic biology in the cosmetic industry, there are still many technical problems existing at different stages of these processes. The yield and the efficiency of the synthesis of complex active molecules or metabolically long active molecules are still far from satisfactory. For instance, it is difficult to synthesize some functional peptides or proteins due to their misfolding or degradation during the synthesis because of their complex structure. Besides, the yield is lowered while their biological activity and the efficacy of the cosmetic products are also at risk because of their misfolding or degradation during the synthesis. Regulation of the impurities during the whole process of microbial fermentation and downstream purification should be further improved. Microbial fermentation may also cause by-products or metabolic wastes; if these impurities are not removed instantly, they will greatly influence the purity and quality of the products and even bring safety risks. Besides, the downstream purification is still a big challenge to widely accept synthetic biology. Simplification of the downstream purification, reduction of cost, and preservation of the purity and activity of the products are still urgent to be improved [19].

5.2. Regulatory Challenges

Since synthetic biology products are a relatively new frontier of modern technology, it is still under development which methods are used to test the safety of synthetic biology products and which regulatory concepts apply to them. Since this field involves extensive reengineering of living systems and manufacturing of new molecules, a rigorous and sophisticated examination and regulation of product safety and potential risks are needed quickly. However, regarding regulation on synthetic biology products, most countries internationally have quite different regulatory policies, and no common or single standard or manual has been developed till now. This leads to a high degree of uncertainty regarding market access upon import and export and compels companies to spend large amounts of money and time adapting to different sets of rules, which in turn raises research and development costs and market entry barriers indirectly. Also the absence of harmonised international standards on 'GMO-in-cosmetics' leads to market access barriers and hampers investment even when technical feasibility has been proven [20].

5.3. Commercialisation Challenges

Commercialisation of synthetic biology in cosmetics is facing many challenges. A large amount of capital must be invested in R&D in order to support laboratory research, strain optimisation and process improvement. This is a major concern for small innovative companies with limited capital. Serious capital investment also has to be made in ramping up production to the industrial level, which involves fermentation tanks, high-capacity equipment and other infrastructure.

The public's understanding of products based on synthetic biology is weak, and people's conceptions about their 'unnaturalness' are quite wide-ranging. This has raised doubts about the safety and effectiveness of these products. Companies should invest in popular science lectures, product experiments and other activities in order to educate the market and raise awareness among the public. Market education and promotion are necessary in order to dispel customers' doubts and gain their trust in synthetic biology products [20].

6. Conclusion

Synthetic biology is revolutionising cosmetics as never before; it's a disruptive technological change. By re-designing microbial cell factories via genetic engineering, most of the issues we face in the traditional cosmetic ingredients production are bypassed, such as sustainability issues, impurity and batch-to-batch inconsistency. New opportunities for innovation in ingredients and potential performance breakthroughs. Currently, the application of synthetic biology in cosmetics encounters some technical issues, at least at this point in time, regulatory issues and commercialisation issues. However, with continued research funding for synthetic biology and gradual development of the regulatory environment, these issues will be obviated in due course.

In the future, the cosmetic industry will increasingly use synthetic biology in order to achieve growth that is green and environmentally friendly. Researchers will continue to develop new gene-editing and metabolic engineering approaches to improve the productivity and efficiency of active molecule production, so as to design new cosmetic ingredients with novel properties. On the other hand, as customers become increasingly environmentally sustainable and conservation minded, cosmetic products of natural origin manufactured economically using synthetic biology will see increasing demand. While that is the case, the governments and regulatory authorities will become increasingly stringent on the regulation of synthetic biology products by developing proper legislation and standards so as to protect consumer rights and consumer safety. Due to the collective effort of all these stakeholders, synthetic biology will form the next wave of cosmetic innovation that gives rise to novel, high performance and environment friendly ingredients that meet customers' needs for sustainability and transparency.

References

- [1] CBNDData. (n.d.). 2025 China consumer trend report. CBNDData.
- [2] Liu, X., Ding, W., & Jiang, H. (2017). Engineering microbial cell factories for the production of plant natural products: From design principles to industrial-scale production. *Microbial Cell Factories*, 16, 1–9.
- [3] Katz, L., Chen, Y. Y., Gonzalez, R., Peterson, T. C., Zhao, H., & Baltz, R. H. (2018). Synthetic biology advances and applications in the biotechnology industry: a perspective. *Journal of Industrial Microbiology and Biotechnology*, 45 (7), 449–461.
- [4] Clomburg, J. M., Crumbley, A. M., & Gonzalez, R. (2017). Industrial biomanufacturing: The future of chemical production. *Science*, 355 (6320), aag0804.
- [5] Bedian, L., Villalba-Rodríguez, A. M., Hernández-Vargas, G., Parra-Saldivar, R., & Iqbal, H. M. N. (2017). Bio-based materials with novel characteristics for tissue engineering applications – A review. *International Journal of Biological Macromolecules*, 98, 837–846.

- [6] Abdi, G., Tendulkar, R., Thatte, C., Mishra, S., Desai, B., Surve, S., Chaudhari, A., Patil, N., Jain, M., & Tarighat, M. A. (2024). Scaling up nature's chemistry: A guide to industrial production of valuable metabolites. *Advances in Metabolomics*, 331–375.
- [7] Rexer, T., Laaf, D., Gottschalk, J., Frohnmeier, H., Rapp, E., & Elling, L. (2020). Enzymatic synthesis of glycans and glycoconjugates. *Advances in Biochemical Engineering/Biotechnology*, 175, 231–280.
- [8] Yan, X., Liu, X., Zhao, C., & Chen, G. Q. (2023). Applications of synthetic biology in medical and pharmaceutical fields. *Signal Transduction and Targeted Therapy*, 8 (1), 1–33.
- [9] Liu, Y., Zhang, D., Yang, T., Chen, R., & Luo, X. (2024). Pathway engineering of plant-derived bioactive compounds in microbes. *Engineering Biology for Microbial Biosynthesis of Plant-Derived Bioactive Compounds*, 73–87.
- [10] Shokoohi, M., & Attar, T. (2024). Biomanufacturing for a sustainable future: Unleashing the potential of biotechnology in pharmaceutical raw material production. *International Journal of New Findings in Health and Educational Sciences (IJHES)*, 2 (2), 142–153.
- [11] Mukhriza, T. (2024). Microbial hyaluronic acid production: A comprehensive review of strategies, challenges and sustainable approaches. *Journal of Biotechnology*, 9 (2), 112–125.
- [12] Gohil, N., Bhattacharjee, G., Khambhati, K., Braddick, D., & Singh, V. (2019). Engineering strategies in microorganisms for the enhanced production of squalene: Advances, challenges and opportunities. *Frontiers in Bioengineering and Biotechnology*, 7, 50.
- [13] Li, M., Chen, R., Qiao, J., Li, W., & Zhu, H. (2025). Recent advances in multiple strategies for the biosynthesis of sesquiterpenols. *Biomolecules*, 15 (5), 664.
- [14] Singla, A., Gupta, O. P., Sagwal, V., Kumar, A., Patwa, N., Mohan, N., Ankush, Kumar, D., Vir, O., Singh, J., Kumar, L., Lal, C., & Singh, G. (2024). Beta-glucan as a soluble dietary fiber source: Origins, biosynthesis, extraction, purification, structural characteristics, bioavailability, biofunctional attributes, industrial utilization, and global trade. *Nutrients*, 16 (6), 900.
- [15] Snetkov, P., Zakharova, K., Morozkina, S., Olekhovich, R., & Uspenskaya, M. (2020). Hyaluronic acid: The influence of molecular weight on structural, physical, physico-chemical, and degradable properties of biopolymer. *Polymers*, 12 (8), 1800.
- [16] Rizzo, M. G., Palermo, N., D'amora, U., Oddo, S., Guglielmino, S. P. P., Conoci, S., Szychlinska, M. A., & Calabrese, G. (2022). Multipotential role of growth factor mimetic peptides for osteochondral tissue engineering. *International Journal of Molecular Sciences*, 23 (13), 7388.
- [17] Garnick, R. L., Solli, N. J., & Papa, P. A. (1988). The role of quality control in biotechnology: An analytical perspective. *Analytical Chemistry*, 60 (23), 2546–2557.
- [18] Budzianowska, A., Banaś, K., Budzianowski, J., & Kikowska, M. (2025). Antioxidants to defend healthy and youthful skin—Current trends and future directions in cosmetology. *Applied Sciences*, 15 (5), 2571.
- [19] Sze, C., Lin, K., Koutinas, A. A., Vlysidis, A., Pleissner, D., Kopsahelis, N., Garcia, I. L., Kookos, I. K., Papanikolaou, S., & Kwan, T. H. (2014). Valorization of industrial waste and by-product streams via fermentation for the production of chemicals and biopolymers. *Chemical Society Reviews*, 43, 2587–2627.
- [20] Li, J., Zhao, H., Zheng, L., & An, W. (2021). Advances in synthetic biology and biosafety governance. *Frontiers in Bioengineering and Biotechnology*, 9, 598087.