Development of Economical Food Products employing Synthetic Biology

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Abstract

Considering global issues pertaining to rapidly growing population, resource scarcity, and economic inequality, the search for affordable food products is increasing. Food production could be transformed by synthetic biology, a rapidly growing field that combines biology and engineering. Designing and engineering biological systems using synthetic biology enables more sustainable and efficient food products and ingredients. This includes specially adapted cultures with improved nutritional composition, optimized production methods and genetically modified microbes for precise fermentation. These technological advances have the potential to reduce production costs, reduce resource use and improve environmental impact, all of which help reduce food prices for people around the world. However, issues of safety, regulation and public acceptance must be resolved before synthetic biology can be widely used in the food sector. This chapter emphasizes the necessity for a balanced strategy that considers both the advantages and disadvantages of this technology.

I. Introduction

In today's rapidly evolving world, emerging trends and contemporary challenges are propelling biology into an exciting new era where effective and tailored solutions are the focus. Beyond our fundamental understanding of life, biological sciences have expanded their scope, embracing established principles and cutting-edge technologies to foster interdisciplinary collaboration among biology, chemistry, physics, engineering, and computational sciences. At the forefront of this convergence lies synthetic biology, a discipline dedicated to ushering in a new technological age where these diverse fields seamlessly merge and complement one another. Synthetic biology, in essence, involves designing and constructing novel biological components, devices, and systems that do not naturally exist while also reshaping existing biological systems to perform specific functions. What sets synthetic biology apart from conventional genetic manipulation techniques is its ability to achieve high-throughput assembly and the engineering of organisms with specific genotypic traits governing the synthesis of intricate, biologically inspired systems, showcasing functionalities that are unparalleled in the natural world (1).

The need of the hour is to produce food products via synthetic biology because of certain reasons such as rapidly rising global population indirectly increasing the food demand in the 21st century. Another global challenge is ensuring sustainable food for the entire human population. Recent events, such as the disruptions in supply chains caused by the SARS-CoV-2 pandemic and geopolitical instability, have underscored the urgency of this issue. It is likely that these challenges will persist and intensify in the face of climate change. Addressing this complex problem requires collaboration among researchers, policymakers, and politicians to devise solutions that can provide sustainable food to everyone on Earth. However, these challenges extend beyond food production alone. Factors like food preservation, packaging, and logistics also play crucial roles and present opportunities for synthetic biology to contribute to the creation of more sustainable foods. It is a delicate balancing act in order to meet the demands of rising populations while also addressing issues like sustainability, environmental effects, and resource constraints. Science and innovation have stepped in to offer fresh ways for navigating this difficult environment. Synthetic biology is one such ground-breaking area that has enormous potential (2).

Utilising cell-free biosynthesis platforms, engineered microbial consortiums, or programmable monoclonal cell factories, synthetic biology enables the enhancement of food production. Future applications of synthetic biology technology may make it feasible to do away with the restrictions of conventional agriculture and animal husbandry in addition to increasing the efficiency of resource conversion for food production. In general, the food industry powered by synthetic biology has the potential to deal with the problems of a sustainable food supply in the future. The current and coming food revolution, driven by synthetic biology, will be covered in three main sections of this chapter. The first section discusses how traditional food production and manufacturing may be enhanced by synthetic biology. Second, how may this artificial biology alter the nutritional value of food or offer new capabilities? Third, how synthetic biology will be able to use tailored microbial communities to modify the conventional fermentation food production manner. The main biotechnologies based on synthetic biology that are anticipated to be applied in food in the future are also introduced. The opportunities and difficulties of synthetic biology for the production of food are finally discussed.

II. Synthetic Biology: Foundations and Concepts

A. Definition and Evolution

Synthetic biology (syn-bio) is a vast field that needs to be explored to avail its maximum benefits in the current scenario. It is an advanced field of biotechnology that combines genetic engineering, computer science, mathematics, and engineering modeling to create new biological parts that do not inherent in nature. It aims to develop ideas for creating new biological parts, devices and models, thus imitating nature and creating them in the laboratory (3). Redesigning models from the trash is the main driving force of syn-bio. This entails the inclusion of genetically modified life forms, spanning the domains of genetics and genomics, ranging from systems biology to synthetic applications. Distinguished accomplishments in medical problem-solving, metabolic and energy manipulation, environmental remediation, materials science, and plant biology have been rendered feasible through the advancements in synthetic biology (4).

The term synthetic biology was coined in 1970 by famous geneticist Waclaw Szybalski. During the 1970s, fundamental work was done to enable the development of DNA synthesis and sequencing technologies (5). The origins of synthetic biology date back to the 1960s. Francis Jacob and Jacques Monod provided the assembly of regulatory systems from molecular components.

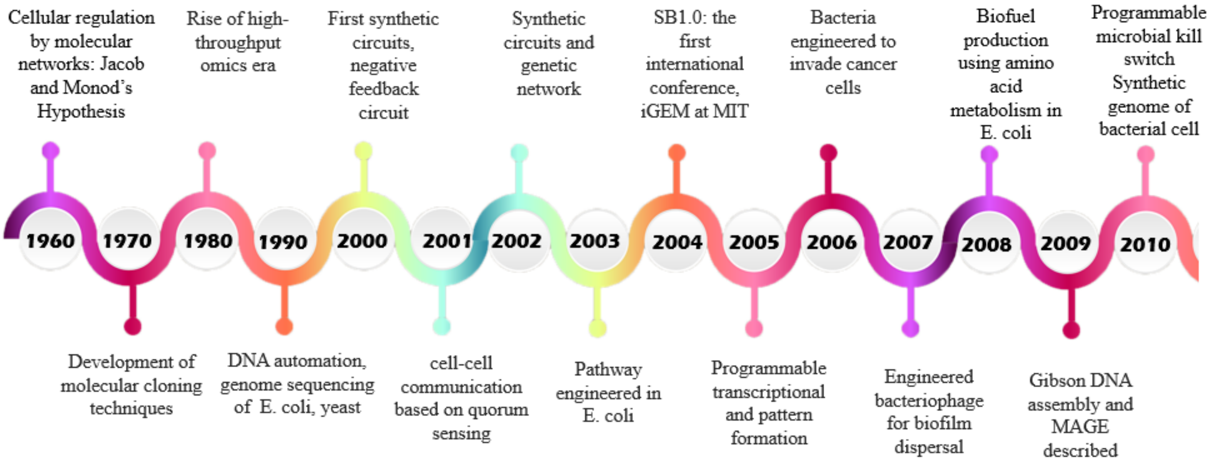

Figure 1- History of Synthetic Biology from Year 1960-2010

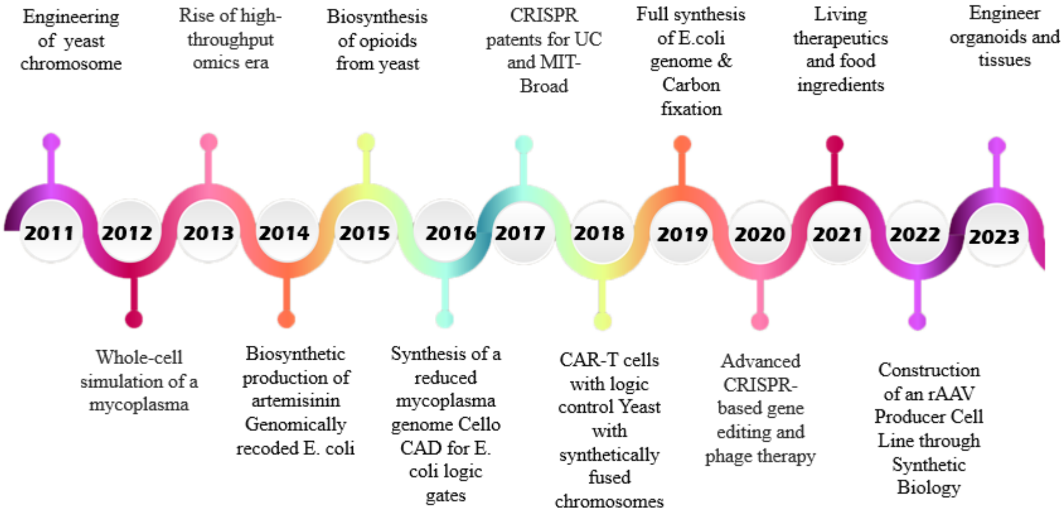

Figure 2- History of Synthetic Biology from Year 2011-2023- The figure 1 and 2 depict the evolving history of synthetic biology from year 1960-2023

B. Principles of Synthetic Biology

This section begins by illustrating the basic principles of synthetic biology to describe the basics of the same. This section focuses on how biological systems are viewed as programmable objects and how standardized genetic building blocks make it possible to construct new biological capabilities. To fully appreciate synthetic biology's disruptive potential in the food sector, it is essential to comprehend these ideas.

The engineering principles of synthetic biology are as follows, enabling for speedy prototyping and the simple sharing of designs across synthetic biologists working in various locations throughout the world. (6).

i. **Modularity** - Modularity is a crucial principle in synthetic biology, enabling the design and construction of components that can be combined to create complex systems. This allows for quick assembly, troubleshooting, reuse of existing parts, safety when working with hazardous materials, and efficient data storage, making it a valuable tool for research and development.
ii. **Standardization** - A key principle in synthetic biology is standardization, which enables more exact design and assembly of biological components and apparatus. Scientists can design systems that are more dependable and reproducible by standardising components like DNA sequences, proteins, enzymes, or other compounds.One such collection of standardised DNA components is the Registry of Standard Biological Parts (BioBricks), which can be assembled together like a set of building bricks to produce new biological systems (6).
iii. **Abstraction** - Abstraction simplifies data storage by providing a common language for describing biological systems, enabling easy sharing of designs, and ensuring safety when working with potentially hazardous materials like GMOs through clear guidelines. It helps in the reduction of development time and cost thereby, increasing accuracy and precision (7).

III. Tools and Techniques- Design-Built-Test-Learn cycle

A. Design -build-test-learn Cycle

The fundamental framework of synthetic biology relies on the iterative process known as the design-build-test-learn cycle. This cycle is extensively employed in the enhancement of microbial platforms, finding significant utility within the food industry. In the realm of synthetic biology, contemporary approaches encompass diverse mechanisms and strategies aimed at effectively reengineering cellular machinery to optimize industrial outcomes. The workflow in synthetic biology is fundamentally rooted in the design-build-test-learn cycle (8).

The DESIGN process involves biological and operational design, specifying desired cellular target functions and determining optimal sample amounts and performance specifications. To implement these functions, appropriate biological parts must be identified and assembled. Standard registries are needed to characterize biological parts under various contexts and conditions. New mathematical and computational tools are needed to solve optimization problems and specify constraints. Design-of-experiment (DoE) approaches can efficiently search for and assemble genetic parts and circuitry, but still require choices and computational methods. As a consequence, DNA sequences with several genetic components are produced, which provide desirable activities in certain biochemical, cellular, organismal, or biome contexts (9).

The BUILD process in involves a sequence of operations, commencing with the assembly of DNA and its subsequent integration into a host organism, followed by the validation of the assembled genetic sequence within its intended genomic context. This iterative process entails the fusion of multiple DNA fragments through molecular biology techniques, facilitated by automated robotic systems. The constructed genetic entities are rigorously confirmed through procedures such as DNA sequencing, restriction enzyme digests, and computational tools. Furthermore, it encompasses the delivery of the genetic constructs into the host organism, either as independent genetic entities or through chromosomal integration. To enhance the efficiency of this transformation process and cell selection, automation and high-throughput screening methods are often employed. (9).

During the TEST process, researchers assess the performance and usability of the synthetic system throughout the testing phase. This entails running tests to see whether the biological construct was created to perform as expected. Researchers can track the synthesis of specific molecules, monitor how the system reacts to In the context of strain screening and phenotypic profiling, various technologies have been applied, including the biology phenotype chip, high-throughput screening using microplates, microfluidics, the fluorescence-activated droplet sorting system (FADS), Raman spectroscopy, Fourier transform infrared spectroscopy, near-infrared spectroscopy, and advanced spectral sensors (10).

The Learn process of the DBTL cycle involves the data analysis and visualization of omics data and modeling for the beginning of the next DBTL cycle. Analysation of data is done by various bioinformatics and machine learning approaches. Various databases have been established such as BioModels, BiGG Models and Kbase for the understanding of various microbes. The integration of these analysis tools and the result display provides us with web page visualization (11).

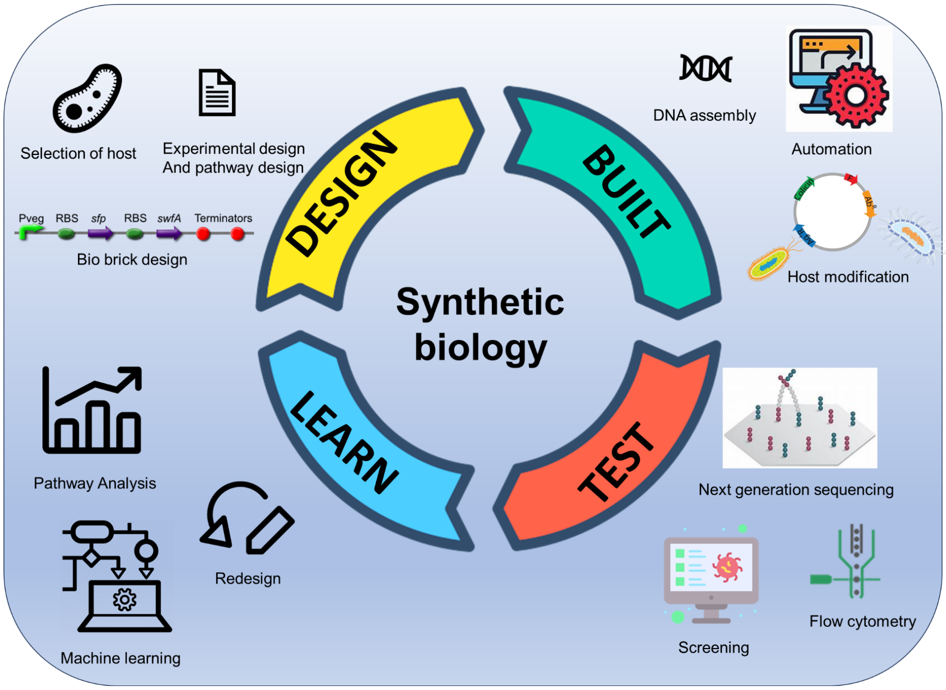

Figure 3 Design-Built-Test-Learn Cycle of Synthetic Biology- The figure represents DBTL cycle of synthetic biology

Synthetic biology is advancing the development of tools and methodologies with the aim of enhancing control over regulatory interactions, as well as interactions with the cellular environment. This progress is ultimately expected to culminate in an integrative synthetic biology framework that enables comprehensive cellular optimization from the ground up. This overarching objective can be delineated into three primary tiers: i) Engineering the central dogma process, ii) Manipulating and controlling transcription, and iii) Modulating translation and protein regulation. Each of these tiers represents concerted efforts to govern cellular systems and harness cutting-edge tools and methodologies. Ultimately, the integration of these approaches will pave the way for the realization of the vision of (12).

The precise control of gene expression is a pivotal prerequisite for the successful establishment of functional genetic circuits within cells, constituting the initial step in the process of cell engineering to confer novel functions. Synthetic biology draws its inspiration from the discipline of engineering genetic circuits, which can function either in isolation within cells or collaboratively as integrated components within the cell's intrinsic biological networks.

To enable autonomous functionality within cells, genetic circuits are frequently designed to be orthogonal to the host, meaning that the control elements regulating these genetic circuits do not intersect with the host's native signaling pathways. These genetic circuits integrate underlying Boolean logic gates, dictating the timing, duration, and functionality of these circuits, all of which can be governed by specified trigger inputs.

In the ensuing sections, we delve into the research tools employed in the realms of molecular biology and genetic engineering.

1. **Genetic circuit** - Early synthetic biology work is focused on constructing genetic circuits by assembling gene regulatory parts to reprogram cells, using proteins like LacI and TetR. These proteins were fused with regulatory domains to control gene expression. Small molecule inducers like IPTG and tetracycline could reverse their effects. These tools enable flexible gene expression control, used for toggle switches, oscillators, and more. Small molecule inducers, however, have limitations in spatial and temporal control.

Optogenetics, using light-sensitive proteins to activate genetic pathways, has emerged to address these issues. It provides precise control over gene expression, promising applications in biomedical engineering (13).

2. **Chassis -** In synthetic biology, a "chassis" refers to the fundamental biological system or organism that serves as the foundational platform for the construction and implementation of engineered genetic circuits and biological components. Much like a car chassis provides the structural framework upon which various automotive parts are assembled, a biological chassis organism, which can range from bacteria to mammalian cells, offers a biological foundation for synthetic biologists to integrate and express engineered genetic elements. The choice of chassis organism depends on multiple factors such as genetic manipulability, compatibility with the desired function, and the specific objectives of the synthetic biology project. Chassis organisms are essential for creating customized biological systems that can be tailored for diverse applications, including the production of biofuels, pharmaceuticals, and environmental sensing (14).
3. **Transcriptional Engineering:** Synthetic biologists are exploring natural transcription networks within cells to understand and harness them for controlling genetic circuits. They seek to activate genetic circuits using novel triggers found within cells to detect diseases, engineer new cellular functions, and enable autonomous cell decision-making. DNA-targeting proteins like Zinc finger (ZF) proteins and transcription activator-like effectors (TALEs) can be engineered to bind specific DNA sequences, regulating the expression of genes. Furthermore, the CRISPR/Cas9 system, when modified (dCas9), enables precise transcriptional control in bacterial and mammalian cells through the design of guide RNAs (gRNAs) that direct Cas9 to target DNA sequences. This technology holds promise for various applications, including regenerative medicine, due to its sequence-specific and precise control of cellular behavior (15).

IV. Significance in Food Production

Synthetic biology revolutionizes food production and enhances food security. This cutting-edge technology is transforming the way food is grown, processed, and delivered to people around the world (16). There are certain reasons to synthesize products using synthetic biology, some of which are described below:

1. This technology can be used to create new food sources for example, scientists are working to create proteins from plants that could be used to make meat alternatives. This would reduce the global demand for animal-based proteins and reduce the environmental impact of livestock production.
2. Improve the nutritional content of existing crops.
3. Reduce the environmental impacts of food production. For example, scientists are using synthetic biology to engineer drought-resistant crops. This can help farmers produce more food in dry climates and reduce the risk of crop failure due to drought.
4. Increase in crop yields by focusing on modified crops resistant to pests and disease.

5. It can be used to improve food safety. Scientists are developing new ways to detect and eliminate food-borne pathogens, which can help to reduce the risk of food-borne illness.
6. It can also be used to develop food packaging that can provide better protection against spoilage.

V. Major Challenge of synthetic biology - Food affordability

It has been observed that there exists a significant global interconnection between malnutrition and the affordability of food. The challenge of malnutrition crises arises primarily due to the unavailability of nutrient-rich foods at prices that are within reach for many individuals. Research has established a strong link between food prices and food insecurity, particularly in developing nations. Notably, food prices have been on a steady rise worldwide, especially over the recent decades. However, research regarding the correlation between food prices, affordability, and food insecurity within the United States is limited. It is noteworthy that food insecurity is most prevalent in the Southern region of the United States, where food prices are comparatively lower, yet incomes are also at the lower end of the spectrum. Variations in food costs within this region may also play a contributing role. Temporal associations have been identified between food prices, consumer spending, and food insecurity. For instance, when food prices in the United States witnessed an increase at the start of the millennium, it resulted in reduced food expenditure among households with low and moderate incomes (17).

Additionally, the International Network for Research, Monitoring, and Action Support on Diet, Obesity, and Non-Communicable Diseases (INFORMAS) is a global network comprising public interest organizations and researchers. This network is dedicated to the tracking, comparison, and facilitation of both public and private sector efforts aimed at fostering the creation of healthy diets, improving environmental factors, and reducing obesity, non-communicable diseases, and associated disparities (18).

A. Role of Technology in Food Affordability

The modern food industry uses a variety of complex technologies, including agricultural machinery, robotics, blockchain, microwaves, evaporators, metabolic engineering, ultrasound, nanotechnology, ozone, enzymes, computer simulations, and computer networks. These technologies have significantly increased productivity and reduce human labor in various manufacturing sectors. Automation has been used to detect delays and waste in the supply chain, while microwave heating and evaporators are widely used in food processing. Metabolic engineering has been used to produce carotenoids using yeast cells, while ultrasound provides hygienic and non-invasive measurements. Nanotechnology has revolutionized agriculture and food systems, while ozone disinfects drinking water and swimming pools. Enzymes, natural catalysts for chemical reactions, are used in industry and the food industry. Computer simulations are used in R&D to solve complex operational problems, and computer networks such as the Internet support the global food movement (19).

V. Application of synthetic biology in food production in agriculture

Global food security is currently confronted with substantial threats, primarily attributable to the rapid expansion of the world's population, the impacts of climate change, conflicts, and notably, the global COVID-19 pandemic that has swept across the world over the past two years. In 2022, the Food and Agriculture Organization of the United Nations (FAO) issued its most recent research report, titled "The State of Food Security and Nutrition in the World 2022." According to this report, approximately one-third of the global population continues to grapple with food insecurity. Simultaneously, the growth rates of key crop yields have stagnated in recent years, with limited prospects for expanding arable land. Consequently, an urgent imperative exists to identify expeditious and sustainable approaches for augmenting agricultural output and enhancing crop nutrition within the constraints of limited arable land to safeguard future food security (20).

Plant synthetic biology has advanced precision breeding through genome editing, significantly reducing the time required for trait selection. Addressing the need to increase crop nutritional value to combat malnutrition, projects like Golden Rice have incorporated genes to boost provitamin A (beta-carotene) production in rice. However, engineering complex traits and pathways for other essential compounds demands synthetic biology approaches. Carotenoids and their derivatives, xanthophylls, offer diverse health benefits, including eye and cardiovascular health, immune support, cognitive function, and antioxidant properties. Astaxanthin, a valuable red keto carotenoid in the fish industry, is primarily synthesized synthetically, but exploring plant-based sources for fish feed is promising. A deeper understanding of regulatory mechanisms controlling astaxanthin and fatty acid biosynthesis is pivotal for future engineering strategies in this domain (21). Synthetic biology in food production has many opportunities, such as:

First, a longstanding objective in plant-based agriculture has been the enhancement of nitrogen fixation, as obtaining bioavailable nitrogen for crops is not only prohibitively expensive but also environmentally taxing, accounting for approximately 1% of the total global annual energy consumption. Unlike plants, microbes, particularly rhizobia in legumes, possess the capacity to fix atmospheric nitrogen. Notably, a collaboration between Gingko Bioworks and Bayer, known as Joyn Bio, is focused on reducing global fertilizer usage by one-third. Their strategy involves the engineering of the plant microbiome to enhance nitrogen fixation in microbial species associated with crops. Additionally, significant endeavors are underway to enable direct nitrogen fixation in higher plants and establish novel symbiotic relationships with nitrogen-fixing bacteria.

Pivot Bio has developed a biological nitrogen fertilizer for corn, named Proven. This innovative product is based on a γ-proteobacterium, KV137, which forms associations with corn roots and possesses the necessary genes for nitrogen fixation. However, these crucial genes are typically inactive when most needed. Synthetic biology techniques have been employed to activate these genes, leading to the restructuring of the KV137 genome. This bacterium serves as the key component in the liquid fertilizer PROVEN, which reduces the requirement for chemical fertilizers by 25 pounds per acre while concurrently boosting yields by 5.8 bushels. Importantly, unlike chemical fertilizers, PROVEN mitigates nitrogen leaching into groundwater, a significant source of pollution, and prevents the release of the potent greenhouse gas N2O into the atmosphere. In 2020, PROVEN was implemented on 250,000 acres, with plans for expansion to millions of acres in 2021 (23).

Second, improvement includes nutritional value of food by biofortification. Biofortification is a process in which the nutritional quality of food crops is improved through agricultural practices or biotechnology to increase the concentration of essential vitamins and minerals in the edible parts of those crops. The goal of biofortification is to enhance the nutritional value of staple crops, such as rice, wheat, maize, and cassava, to address specific nutrient deficiencies in populations, particularly in regions where people rely heavily on these crops for their diets. Plant synthetic biology holds great potential for addressing malnutrition, particularly micronutrient deficiencies known as "hidden hunger." This includes deficiencies in vitamins A, iodine, zinc, and iron, which affect a significant portion of the global population. To combat this issue, researchers are exploring the biofortification of crops to make them more nutrient-rich and adaptable to various environments. Traditionally, crop improvement involved time-consuming breeding practices, but the advent of gene-editing technologies like CRISPR-Cas9 allows scientists to directly modify plant DNA within a single generation, bypassing lengthy breeding processes (24). Examples of this technology include enhancing ground cherries and domesticating wild tomatoes to improve their nutritional content while maintaining disease resistance. These advancements could lead to the cultivation of previously challenging plant species as crops, expanding food choices and increasing nutrient availability worldwide. Additionally, incorporating nutraceutical compounds like resveratrol into our diets can promote better health. Resveratrol, found in plants like wine and chocolate, offers cardiovascular and diabetes-related health benefits. However, its low concentration in native plants and high metabolism when consumed in isolation pose challenges. To address this, researchers are exploring ways to add resveratrol to foods, making their delivery more efficient. Most plants contain precursor molecules for resveratrol, and modifying a single gene can enable its production in various plants. Optimization of precursor pathways is essential to increasing nutraceutical levels in specific foods.

The third major area of focus involves the enhancement of photosynthesis. This biological process is unique in its ability to utilize light energy to generate chemical energy for the synthesis of complex carbon compounds. Photosynthesis serves as the fundamental driving force in agriculture and stands as the defining characteristic of green lineage organisms. However, it is inherently inefficient, with a theoretical maximum efficiency of approximately 11%, typically not surpassing a few percent. Consequently, there exist numerous potential targets within the domain of synthetic biology to enhance its performance.

One strategy, for instance, entails the introduction of cyanobacterial carboxysomes into chloroplasts, potentially addressing the suboptimal activity of RuBisCO, the enzyme responsible for carbon dioxide fixation during photosynthesis. The feasibility of this approach has been successfully demonstrated by localizing β-carboxysomal proteins, resulting in the self-assembly of empty carboxysomal microcompartments within Nicotiana benthamiana chloroplasts. This capability to augment the capacity and efficiency of plants in capturing atmospheric carbon holds substantial implications for agricultural productivity and the management of natural resources.(23).

Lastly, the challenge within plant-based agriculture pertains to land use. Global land availability is constrained by factors such as suitability for commercial agricultural exploitation and contamination resulting from industrial processes that render potentially arable land unsuitable. Two potential strategies are being explored to address this issue: bioremediation using microbes and the genetic engineering of plants for growth in non-arable land.

Bioremediation involves the use of biological systems to alter an environment. Some success has been achieved in using wild isolates of organohalide-respiring bacteria (ORB), like Desulfmonile tiedjei, for the bioremediation of organohalides. Researchers are now extending this concept to rational engineering approaches applicable to agriculture. This includes the transformation of microbes like S. cerevisiae and Escherichia coli into potential bioremediation agents, capable of addressing heavy metal contamination, the degradation of toxic aromatic compounds, and the generation of biomass-based sugars.

The second strategy involves the engineering of new cultivars suitable for non-conventional environments. This has become increasingly feasible due to the availability of genome sequences of various cultivars and lesser-known organisms. By leveraging the genomic information from resilient cultivars, it is possible to reverse engineer plants to withstand abiotic stresses. The reverse engineering of traits such as halotolerance from candidate plants like the aquatic and salt-tolerant angiosperm Zostea marina into crop plants could play a transformative role in regions affected by salinity and assist in regenerating non-arable land. Similar reverse engineering strategies can also be employed to integrate proven microbial solutions directly into higher plants (23).

VI. Challenges of Synthetic Biology in Agriculture

Agricultural crop productivity is primarily determined by three crucial factors: the effectiveness of capturing light energy, the efficiency of converting this light energy into plant biomass, and the harvest index, which represents the portion of total energy within plant biomass that is found in the harvestable organs. Notably, the efficiency of light energy capture and the harvest index have essentially reached their inherent biological constraints. In contrast, the conversion efficiency currently stands at just 20% of its theoretical maximum, offering a promising target (24) for engineering improvements. Nevertheless, the manipulation of these complex traits remains a challenging endeavor.

The main challenge in implementing synthetic biology in agriculture is the time and cost involved in propagating, transforming, and screening higher plants. Despite advancements such as CRISPR/Cas9-mediated gene editing, speed breeding techniques, genome sequencing of key plants, and the growth of synthetic biology as a field, significant obstacles remain. Plant genomes are often large and polyploid, limiting the effectiveness of precise genetic manipulation. Moreover, compared to microbes, plants typically have less efficient homology-directed recombination mechanisms. Additionally, it is essential for primary industries to consider consumer attitudes toward genetic manipulation, especially in the context of food production (25).

VII. Safety and Regulation

The European Food Safety Authority (EFSA) has identified potential risks, which encompass the exacerbation of weed issues, the displacement and possible extinction of indigenous plant species. These concerns are of particular significance as they might not be adequately addressed within the scope of environmental risk assessment (ERA) conducted by EFSA. This is due to the fact that EFSA's assessment primarily focuses on the inherent traits of the initial events, while potentially overlooking unforeseen or unintended consequences that may arise from subsequent propagation and gene flow. (26).

FSSAI and FDA approvals are currently in progress for the approval of the products developed by synthetic biology thereby ensuring food safety. Several research centers in synthetic biology were established, including eight members of the Global Biomolding Alliance, in the Asia region. An inter-regional organization called Asian Synthetic Biology Association (ASBA) was also established to promote its scholarly communication, collaboration and technology commercialization (27).

VIII. Bioeconomy and Environmental Impact

During the later half of the twentieth century, genomic advancements primarily centered around healthcare applications. A report by the OECD revealed that, as of 2003 when the Human Genome Project was published, only a minimal 2% of biotechnology investments were directed toward industrial biotechnology. This figure increased modestly to just 6% by 2010, in stark contrast to the dominant 80% allocated to the health sector (28). Since then, the biotechnology market has witnessed substantial growth. According to a recent study by Grand View Research, Inc., the global biotechnology market, valued at approximately USD 370 billion in 2016, is projected to reach USD 727 billion by 2025, reflecting an impressive annual growth rate of 7.4% . This report highlights key factors fueling this financial expansion, such as regenerative medicine and genetics in diagnostics, which incorporates artificial intelligence to enhance patient-specific diagnoses through a deeper analysis of population data.

Additionally, the report identifies supportive government policies related to synthetic biology as a major driver of growth in the biotechnology sector. It acknowledges that developed economies like the UK and the USA are closely monitoring and funding synthetic biology research and development initiatives. The recent introduction of the UK Bioeconomy Strategy reaffirms the UK's ongoing commitment to supporting this technology.

The evolution of synthetic biology as a distinct approach can be traced back to the 2004 SB 1.0 conference, which initiated a 'parallel track' of developments. These developments were not solely focused on healthcare delivery but aimed at establishing a foundational platform for technology rooted in engineering principles. This approach has led to the development of efficient bio-design and bio-manufacturing capabilities, opening a much broader range of potential applications across the entire bioeconomy. In the years since, numerous synthetic biology SMEs and start-ups have emerged, offering valuable resources for exploring and developing innovative solutions and providing essential training for future skilled workforces (28).

A. Environmental Impact

Current agricultural practices are widely recognized for their role in elevating greenhouse gas emissions, a significant driver of climate change. Acknowledging these environmental impacts, the White House's Inflation Reduction Act in 2022 has put forth several eco-friendly agricultural options as a means to mitigate emissions. Among these recommendations are the provision of financial incentives to encourage the adoption of sustainable practices and the promotion of climate-smart land management. While these initiatives mark important strides in lessening the environmental impact of agriculture, there remains substantial potential for further improvement.

The inherent predicament with conventional agricultural methods lies in their substantial emissions of greenhouse gases, which contribute to global warming. Synthetic biology offers the promise of reducing this environmental footprint by minimizing waste generation. Agricultural byproducts can be repurposed as feedstock for bioreactors, yielding a spectrum of valuable bioproducts, including bioactive compounds. The significance of current farming practices in exacerbating ongoing climate challenges is noteworthy. In 2020, the agricultural sector in the United States alone released an estimated 669.5 million metric tons of gases that are equivalent to carbon dioxide. Notably, 50.5% of this total stemmed from nitrous oxide emissions resulting from fertilizer use, while methane emissions from cattle and livestock accounted for 37.5% of greenhouse gases in the same year. Additionally, the carbon footprint attributed to the fuel consumption of agricultural machinery further contributes to the environmental impact (29).

B. Reducing Environmental Footprint

Synthetic biology has the potential to significantly reduce the environmental footprint of food production. By optimizing metabolic pathways in microorganisms, it can lead to more efficient production processes. This means fewer resources are required for the same output, resulting in reduced land use, water consumption, and energy usage. Additionally, the controlled cultivation of engineered microorganisms in bioreactors can minimize habitat disruption and soil degradation associated with traditional agriculture (30).

C. Waste Reduction and Circular Economy

One of the key principles of synthetic biology is the ability to engineer microorganisms to utilize waste materials as feedstock. In the context of food production, this means converting agricultural and food processing waste into valuable products. This not only reduces waste disposal problems but also creates a circular economy where waste becomes a resource for producing food and other valuable compounds. This approach aligns with sustainable practices by minimizing waste generation and promoting resource efficiency (1).

D. Carbon and Resource Efficiency in Food Production

Synthetic biology can lead to greater carbon and resource efficiency in food production. Engineered microorganisms can be designed to produce specific food ingredients with minimal resource inputs, reducing greenhouse gas emissions associated with traditional agricultural practices. In summary, synthetic biology offers innovative solutions to address the environmental challenges associated with food production. It can help reduce the environmental footprint, promote a circular economy, and enhance carbon and resource efficiency in the quest for sustainable and environmentally friendly food systems (1).

IX. Global Market Trends Overview of Synthetic Biology

Synthetic Food Market size reached USD 16 billion in 2022 and is anticipated to exhibit a CAGR of 7% between 2023 and 2032, because of the increased interest in artificial foods as meat replacements. The prominent players are BASF, Bayer, Precigen, Amyris, Gingko Bioworks, Pivot Bio, Mosa Meat, and Twist Bioscience. Artificial food is an increasingly popular trend, with advances in synthetic biology supporting the development of a new line of ultra- processed, synthetically produced foods. These new products seek to replace and imitate animal proteins, food additives, and other rare ingredients. The growing attraction toward alternative proteins will provide an edge to synthetic biology food developers, considering their ability to replicate the taste, appearance, and texture of meat. Consumers are also gaining awareness of the limitations of meat and traditional protein, enabling synthetic food to emerge as a viable alternative (31).

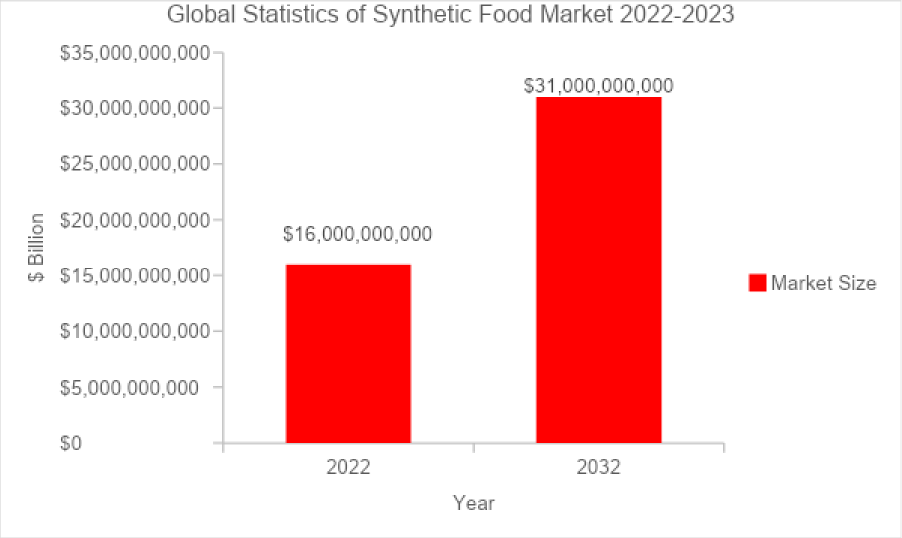

Figure 4 Global Statics of Synthetic Food Market- The diagram illustrates worldwide statistics pertaining to the synthetic food market for the period spanning 2022 to 2023. **(Source: https://www.gminsights.com/industry-analysis/synthetic-food-market)**

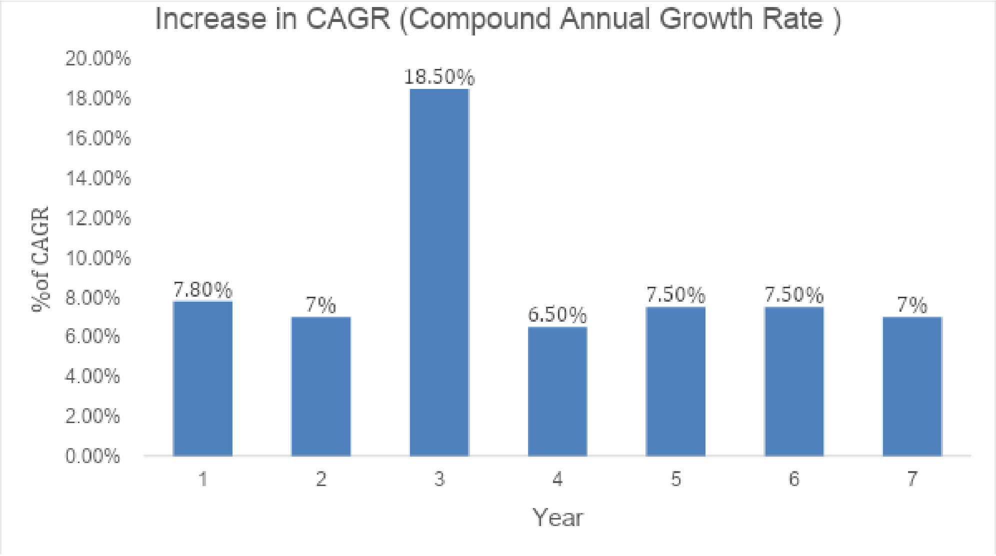

Figure 5 Increase in CAGR (Compound Annual Growth Rate) of different industries- The chart displays the Compound Annual Growth Rate (CAGR) data for various food industries over successive years. **(Source: https://www.gminsights.com/industry-analysis/synthetic-food-market)**

Artificial food is an increasingly popular trend, with advances in synthetic biology supporting the development of a new line of ultra- processed, synthetically produced foods. These new products seek to replace and imitate animal proteins, food additives, and other rare ingredients. The growing attraction toward alternative proteins will provide an edge to synthetic biology food developers, considering their ability to replicate the taste, appearance, and texture of meat. Consumers are also gaining awareness of the limitation of meat and traditional protein, enabling synthetic food to emerge as a viable alternative (31).

The global market for synthetic biology in agriculture and food holds a substantial presence within various nations across North America and Europe. In this context, North America takes a lead position in this global market, with a high degree of market penetration observed in both the United States and Canada. These regions are anticipated to demonstrate robust market growth over the forthcoming five years. Throughout the projected period from 2020 to 2025, the Asia-Pacific and Japan region is poised to emerge as one of the most promising markets for synthetic biology in agriculture and food. This anticipation stems from the recognition of significant growth prospects in this region, underpinned by an increasingly optimistic economic outlook in these countries. Notably, the nations within this geographical area offer considerable opportunities for market expansion, attributed to a growing urban population, the widespread adoption of advanced technologies, and supportive government investments aimed at fostering the implementation of innovative agricultural technologies (31).

X. Social Acceptance and Consumer Perception

Public perceptions of synthetic biology are ambivalent, with enthusiasm for applications addressing societal, medical, and sustainability needs. However, concerns arise about DNA manipulation without sufficient funding for long-term implications. Participants remain skeptical about futuristic technological visions and support funding for applications that meet social and sustainability goals. Oversight priorities include transparency, accountability, and tailored governance with independent checks and balances (31). People tend to have negative attitudes towards the food products developed via synthetic biology. People's attitudes vary toward biotechnology, which affects consumer acceptance or rejection of the technology. Diverse public perceptions exist regarding biotechnology, significantly impacting consumer receptivity or resistance to this technology. Public sentiment toward emerging or contentious scientific topics can result in the rejection of specific technologies. This sentiment is influenced by a multifaceted interplay of factors, which at times are competing and at other times complementary. These factors encompass sociodemographic variables, personal ideologies, assessments of risk versus benefit, prior knowledge, and the framing of issues by the media (32). Additionally, a transregional entity known as the Asian Synthetic Biology Association (ASBA) has been established with the primary objective of fostering academic discourse, collaboration, and the commercialization of technology in the realm of synthetic biology. (33)

XI. Challenges in Synthetic Biology

The chapter includes definition of synthetic biology, its tools, and techniques. While we are currently some distance away from achieving this, synthetic bsyntheticiology holds the potential to allow us to engineer living organisms much like how we design and create everyday appliances such as dishwashers, cars, computers, or airplanes. Just as engineering has significantly enhanced our quality of life by providing us with countless innovations, it has also led to the development of advanced military technologies like bombers, tanks, and even the atomic bomb (3). In a similar vein, Synthetic Biology has the capacity to be harnessed for both constructive and potentially harmful purposes.

A. Biosecurity

The primary concern within the realm of Biosecurity arises when we consider the potential for rogue states or terrorist organizations to engage in the reengineering of microorganisms or living systems with the intention of causing harm. While this notion can be alarming, the actual process of creating a new pathogenic organism and effectively deploying it is far from straightforward. There are numerous uncertainties surrounding what makes a pathogenic organism virulent in a natural environment as opposed to a controlled laboratory setting. For instance, such an organism would need to outcompete other microorganisms and evade the host's immune response to survive and thrive. These obstacles, along with the complex engineering challenges they pose, currently act as significant barriers. However, it's crucial to acknowledge that as scientific advancements continue to progress, these hurdles may be overcome in the not-so-distant future (34).

B. Ethical Issues

Beyond the safety concerns, it is crucial to address the ethical dilemmas surrounding the complete engineering of novel life forms or the modification of existing species. While these activities might not immediately pose biosafety or biosecurity threats, they can elicit significant ethical apprehensions among certain segments of the population, who perceive them as akin to assuming a God-like role. Although we are not presently at the stage where we can seriously contemplate applying synthetic biology to enhance specific traits in target species, including the potential for human modification, such scenarios require meticulous consideration and the establishment of clear regulatory frameworks, akin to those developed for human cloning. While designing new living systems for scientific purposes may not inherently raise major ethical concerns, the prospect of altering human beings demands a comprehensive ethical assessment. It is worth noting that the perception of "playing God" may be a more contentious issue in the United States compared to Europe, where the redesign of living organisms could be viewed with greater concern. Security concerns related to the deliberate release of biological agents are a pivotal aspect in the discourse surrounding the interplay between policy and the industrial applications of synthetic biology. Within this context, the DNA synthesis sector stands as a particularly critical area of concern, given that ordered DNA fragments harbor the potential for misuse. As a result, a comprehensive scrutiny and evaluation of all potential avenues, encompassing customers, is deemed necessary to address these security apprehensions. The security concerns are not new to synthetic biology. Biotechnology and even microbiology also had to deal with these concerns of misuse. Although Martinot and Benner (2004) are confident that artificial genetic systems will not survive outside the lab, research in this field raises profound biosafety questions. Dr. Jonathan King (Pollack,2001), a professor of molecular biology at MIT commented in the New York Times and cautioned that *“It’s a powerful technology, and like all powerful technologies, it needs appropriate oversight and regulation”*. One possible scenario he proposed is that the incorporation of artificial amino acids into proteins might trigger allergic reactions when these proteins are used in pharmaceuticals or food products. Advocates of synthetic biology are optimistic that the potential for a highly environmentally sustainable solution, involving the use of synthetic microbes for cost-effective biofuel production or for mitigating the effects of climate change, will be compelling enough to garner public approval, even in the face of acknowledged risks and hazards(35). Agricultural crop yield is predominantly shaped by three primary factors: the effectiveness of capturing light energy and its subsequent conversion into biomass, as well as the harvest index, which signifies the proportion of total energy within plant biomass that resides in the harvestable organs. Notably, both the efficiency of light energy capture and the harvest index have essentially attained their biological constraints. In contrast, the conversion efficiency currently stands at a mere 20% of its theoretical maximum, offering a viable target for engineering improvements (35). However, the manipulation of such multifaceted traits remains a complex endeavor.

The main challenge in implementing synthetic biology in agriculture is the time and cost involved in propagating, transforming, and screening higher plants. Despite advancements such as CRISPR/Cas9-mediated gene editing, speed breeding techniques, genome sequencing of key plants, and the growth of synthetic biology as a field, certain obstacles remain. Plant genomes are often large and polyploid, limiting the effectiveness of precise genetic manipulation. Moreover, compared to microbes, plants typically have less efficient homology-directed recombination mechanisms. Additionally, it is essential for primary industries to consider consumer attitudes toward genetic manipulation, especially in the context of food production. An ongoing objective in plant-based agriculture is to enhance nitrogen fixation (35).

XII. Conclusion

In conclusion, the development of economical food products through synthetic biology represents a significant and promising advancement in the field of agriculture and nutrition. Synthetic biology, defined as the interdisciplinary field that combines biology, engineering, and computational science to design and construct biological parts, devices, and systems, has opened new avenues for addressing critical challenges in the food industry.

Synthetic biology employs a wide range of tools and techniques, with the most notable being the CRISPR-Cas9 system. This revolutionary gene-editing technology allows for precise and efficient modification of the DNA of various organisms, including crops, to achieve desirable traits, such as increased nutritional content and disease resistance.

Market trends in synthetic biology indicate a growing interest and investment in this field, with a focus on sustainable and environmentally friendly solutions for food production. The application of synthetic biology in agriculture holds great promise, as it enables the biofortification of essential nutrients in crops, addressing malnutrition concerns worldwide. By enhancing the nutritional content of staple crops and enabling the cultivation of previously challenging plant species, synthetic biology has the potential to diversify available food options and increase the availability of nutrients that are limited in various regions.

In summary, synthetic biology offers a powerful toolbox for the development of economical and nutritionally enriched food products. As this field continues to advance, it holds the key to addressing global food security issues and improving the overall health and well-being of communities around the world. The application of synthetic biology in agriculture is poised to play a vital role in the future of food production and nutrition.

XIII. References

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