HSPI Inc. The Open Access Publisher

A B B ARCHIVES OF BIOTECHNOLOGY AND BIOMEDICINE
ISSN 2639-6777

Review Article

Unlocking the Transformative Power of Synthetic Biology

Amaan Arif, Prekshi Garg and Prachi Srivastava*

Amity Institute of Biotechnology, Amity University Uttar Pradesh, Lucknow Campus, 226028, India

Abstract

Artificial Intelligence (AI) combined with Synthetic Biology has the potential to change the way we approach medicine, agriculture, and manufacturing. AI automates tasks, optimizes experimental designs, and predicts biological behaviours, resulting in more efficient design and engineering of biological systems. However, there are challenges such as data limitations, interpretability issues, and ethical considerations like biosafety and biosecurity concerns that need to be addressed. AI can be used to analyze vast amounts of data and identify patterns. This has led to successful applications of AI in high-throughput screening and biomanufacturing, which can drive innovation and address critical challenges. AI-powered closed-loop systems for real-time monitoring and control of biological processes also show promise in providing real-time feedback and optimizing systems on the fly. Despite these advancements, it's important to consider ethical implications to ensure the responsible development and application of AI in synthetic biology. Proper consideration of challenges and ethical considerations can help leverage the power of AI to drive innovation and tackle pressing societal challenges. Overall, the potential of AI in synthetic biology is significant. By addressing challenges and ethical considerations, we can use them effectively to solve pressing problems.

More Information

***Address for correspondence:** Prachi Srivastava, Amity Institute of Biotechnology, Amity University Uttar Pradesh, Lucknow Campus, 226028, India, Email: psrivastava@amity.edu

Submitted: March 11, 2024
Approved: April 17, 2024
Published: April 18, 2024

How to cite this article: Arif A, Garg P, Srivastava P. Unlocking the Transformative Power of Synthetic Biology. Arch Biotechnol Biomed. 2024; 8: 009-016.

DOI: 10.29328/journal.abb.1001039

Keywords: Artificial intelligence; Synthetic biology; CRISPR-Cas9; Predictive modeling; Ethical considerations

Introduction

Synthetic biology is a multidisciplinary field that focuses on the application of engineering principles to biology. Its primary objective is to design and construct novel biological devices, parts, or systems that are either not found in nature or to redesign existing natural systems for practical purposes [1]. The ultimate objective of synthetic biology is to develop live biological systems that can process information, manipulate chemicals, fabricate materials and structures, produce energy, provide food, and maintain and enhance human health. Synthetic biology researchers and companies worldwide are using the power of nature to solve a variety of issues in various fields, including medicine, manufacturing, and agriculture. The field of synthetic biology is rapidly expanding due to the advancement of more robust genetic engineering capabilities and reduced cost of DNA synthesis and sequencing [2]. As a result, synthetic biology is rapidly becoming a major contributor to the scientific community and is poised to contribute to the advancement of fundamental knowledge of biological systems and our environment [3].

Concept of AI and its potential in synthetic biology

Figure 1 provides AI with the potential to enhance synthetic biology research and development significantly. AI is already being used to advance synthetic biology in several ways.

Synthetic biology is a rapidly growing field that involves the design and construction of new biological systems that can perform specific functions. Recent advances in Artificial Intelligence (AI) have enabled scientists to use powerful algorithms to enhance various aspects of synthetic biology research. Here are some specific examples of how AI is being used to transform the field of synthetic biology:

1. **CRISPR-based gene editing**: AI is being used to improve the efficiency and precision of CRISPR-Cas9 gene editing technology. By analyzing large amounts of genetic data, AI algorithms can predict the most effective ways to target specific genes and make modifications to the genetic material [4,5].

2. **Automated experiment design:** AI can help researchers

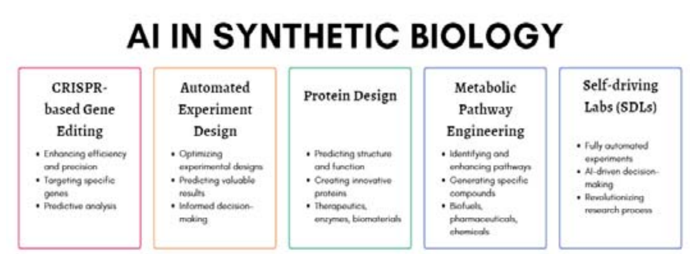

Figure 1: Some specific examples of how AI is being used to transform the field of synthetic biology.

optimize experimental designs by predicting which experiments are most likely to yield valuable results. By analyzing large data sets, AI algorithms can detect patterns and make predictions about how different variables will impact the outcome of an experiment. This can help researchers make more informed decisions about which experiments to conduct and how to design them.

3. **Protein design:** AI is being used to predict the structure and function of proteins, which can help researchers create innovative proteins with specific characteristics. This has applications in therapeutics, enzymes, and biomaterials, and could lead to the development of new treatments for a variety of diseases.

4. **Metabolic pathway engineering**: AI is being harnessed to identify and enhance metabolic pathways for generating specific compounds, including biofuels, pharmaceuticals, and various chemicals. By analyzing numerous data on metabolic processes, AI algorithms can identify ways to optimize these pathways and increase the efficiency of these processes.

5. **Self-driving labs (SDLs):** The concept of self-driving labs combines fully automated experiments with AI that decides the next set of experiments. This has the potential to revolutionize the research process in synthetic biology by enabling scientists to conduct experiments more quickly and efficiently and to make more informed decisions about which experiments to conduct next. AI's potential in synthetic biology is vast, from enhancing experimental designs to enhancing gene editing and protein design. By leveraging AI, researchers aim to expedite the development of new biological systems and address the challenges of medicine, manufacturing, and agriculture.

According to Figure 2, the advantages of employing AI for biological systems include enhanced predictive modelling capabilities, accelerated optimization processes, and improved scalability. The field of synthetic biology has seen significant advancements in recent years, thanks to the integration of Artificial Intelligence (AI) in the research and development process. The use of AI in engineering biological systems offers several advantages that have revolutionized the sector. One of the most significant benefits of integrating AI into biological research is the efficiency it offers. AI-powered systems can automate experiments, optimize operations, and streamline the research and development process, reducing the need for manual labour and reducing the cost and resources [6].

Another major advantage of AI in synthetic biology is the accuracy it provides. AI algorithms can analyze vast amounts of data with high accuracy, identifying subtle patterns and relationships that might be missed by human researchers. This can lead to the discovery of more effective compounds and materials, which can have a significant impact on various industries such as healthcare, energy, and agriculture [7].

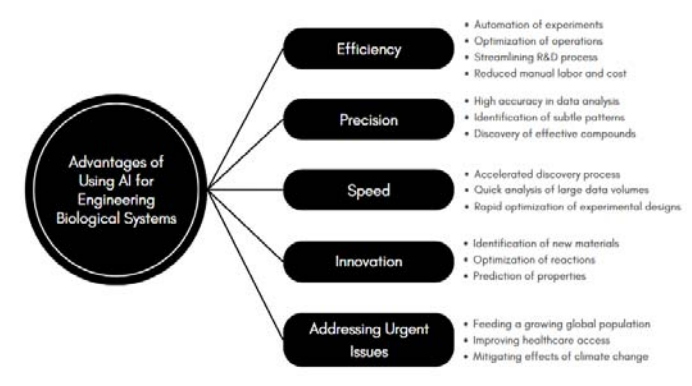

Figure 2: Advantages of Using AI for Engineering Biological System.

Speed is another critical factor that makes AI a valuable tool in synthetic biology. AI can accelerate the discovery process by quickly analyzing large volumes of data and identifying potential new compounds, reducing the time and resources required to complete the drug discovery process. Furthermore, AI can also optimize experimental designs, predict the properties of new molecules, and pinpoint and enhance metabolic pathways for generating specific compounds, such as biofuels, pharmaceuticals, and various chemicals.

Furthermore, AI can assist in identifying new materials, optimising reactions, predicting properties, accelerating the pace of innovation, and reducing the cost and cost of bringing new products to market. The integration of AI in synthetic biology can help researchers tackle some of the most urgent issues, including feeding a growing global population, improving healthcare and access to therapies, and mitigating the effects of climate change [7].

In summary, the use of AI in synthetic biology has opened up new possibilities for scientists and researchers to solve some of the world's most pressing issues. The combination of AI and biological research can lead to more efficient, precise, and innovative solutions, ultimately improving our quality of life and contributing to a better future for all [8].

AI-powered design and optimization

Figure 3 shows the integration of AI for design and optimization in synthetic biology, demonstrating its capabilities in creating novel genetic constructs, optimizing metabolic pathways for bioproduction, and accelerating the development of bio-based materials. These examples focus on the transformative impact of AI in advancing the field of synthetic biology.

AI is used to design novel biological parts and systems

Artificial Intelligence (AI) has emerged as a powerful

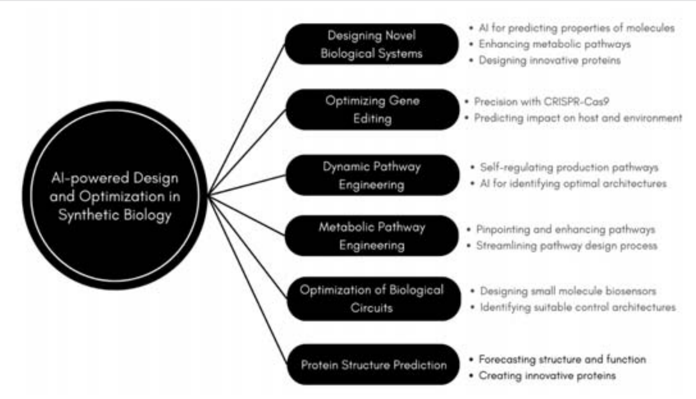

Figure 3: AI-powered Design and Optimization in Synthetic Biology.

tool in the field of synthetic biology, enabling researchers to design and engineer novel biological systems in several ways. One of the significant applications of AI in synthetic biology is optimizing experimental designs, predicting the properties of new molecules, and enhancing metabolic pathways for generating specific compounds. This approach enables researchers to save time and resources by identifying the most promising experimental conditions and predicting the outcomes of experiments accurately [8,9].

Another area where AI is transforming synthetic biology is in the design of innovative proteins. By forecasting the structure and function of proteins using AI algorithms, researchers can create novel proteins with specific characteristics that can be used for therapeutic or industrial purposes. This approach can help unlock new possibilities for drug discovery and protein engineering [9].

AI is also making gene editing more accurate and efficient by enhancing the precision of CRISPR-Cas9 technology. By utilizing AI algorithms to predict the impact of gene editing on the host and the environment, researchers can reduce the risk of unintended consequences and improve the safety of gene editing approaches.

Moreover, AI can be used to predict the impact of bioengineering approaches on the host and the environment, which can help achieve the goal of engineering cells to a specification. This approach can help researchers create cells with specific properties, such as increased productivity or resistance to stress.

Finally, AI can be used to design and construct custom genetic circuits for various industrial applications. By leveraging AI algorithms to optimize the design of genetic circuits, researchers can create circuits with improved functionality and reliability and accelerate the development of biotechnologies for industrial use.

Overall, AI is revolutionizing synthetic biology by enabling researchers to design and engineer novel biological systems faster and more efficiently, addressing pressing challenges in medicine, manufacturing, and agriculture.

AI algorithms for optimizing metabolic pathways, gene circuits, and protein functions

Synthetic biology is a rapidly growing field that involves the design and engineering of biological systems for various applications, including the production of biofuels, pharmaceuticals, and other chemicals. One of the key challenges in this field is the optimization of metabolic pathways, gene circuits, and protein functions to achieve specific production goals. To address this challenge, researchers are increasingly turning to AI algorithms to expedite the design process, identify hidden patterns in complex datasets, and rapidly screen through large collections of designs [10].

One of the most promising applications of AI algorithms in synthetic biology is dynamic pathway engineering. This approach involves designing metabolic production systems that are embedded with intracellular control mechanisms, which enable host cells to self-regulate the temporal activity of a production pathway in response to environmental changes. AI algorithms are employed to identify architectures that optimize production, design synthetic gene circuits, and select optimal architectures in dynamic pathway engineering [10,11].

Another important application of AI algorithms in synthetic biology is metabolic pathway engineering. In this approach, AI algorithms are harnessed to pinpoint and enhance metabolic pathways for generating specific compounds. By forecasting the most effective routes for synthesizing target molecules, AI algorithms can streamline the pathway design process and accelerate the development of new products [12].

AI algorithms are also being used to optimize the architecture of biological circuits, including the design of small molecule biosensors and the selection of suitable control architectures. For instance, AI algorithms have been employed to design synthetic gene circuits and to identify architectures that can support specific production phenotypes.

Finally, AI is utilized to forecast the structure and function of proteins, enabling the creation of innovative proteins with specific characteristics. This can have applications in the development of new enzymes, therapeutics, and biomaterials. For example, AI algorithms have been used to predict protein structures based on amino acid sequences, revolutionizing protein structure prediction.

In summary, AI algorithms offer several advantages in synthetic biology, including the ability to accelerate the design process, identify hidden patterns in complex datasets, and rapidly screen through large collections of designs. By optimizing metabolic pathways, gene circuits, and protein functions, AI algorithms provide powerful tools to expedite the design and engineering of biological systems for various applications.

Over the past few years, the integration of AI and synthetic biology has led to several successful applications in various fields such as biofuel production, drug discovery, and environmental remediation. Companies like LS9 and Verdezyne have used synthetic biology and AI to optimize metabolic pathways for the production of biofuels. By developing capabilities for the computational design and automated parallel construction of gene, operon, and recombinant cell libraries, LS9 enabled the rapid construction and evaluation of engineered pathways. Verdezyne, on the other hand, employed a combination of pathway engineering, which allowed for the rapid creation and harnessing of genetic diversity to optimize biofuel production. The successful integration of AI and synthetic biology has not only paved the way for more efficient biofuel production methods but has also contributed to environmental sustainability [13].

In drug discovery, AI has been instrumental in developing novel, environmentally benign alternative manufacturing routes for pharmaceuticals. Companies like Merck and Codexis have leveraged synthetic biology and AI to achieve this. Codexis collaborated with Merck to develop a transaminase using synthetic biology and directed evolution technologies, which led to a new biocatalytic route for the production of Sitagliptin. Sitagliptin is a first-in-class dipeptidyl peptidase-4 inhibitor marketed as Januvia® for the treatment of type II diabetes. The use of AI and synthetic biology in drug discovery has revolutionized the pharmaceutical industry by enabling the development of new drugs cost-effectively and sustainably.

AI has also been used to predict the environmental impact of new chemicals and materials, enabling researchers to identify compounds that are more sustainable and have a lower environmental footprint. This has the potential to reduce the environmental impact of chemical research and development and support sustainability efforts. The integration of AI and synthetic biology has proved to be a game-changer in the field of environmental remediation [14-16].

In summary, the successful applications of AI and synthetic biology in biofuel production, drug discovery, and environmental remediation have demonstrated the potential of these technologies to address critical challenges and drive innovation. The possibilities are endless, and there is no doubt that AI will continue to play a vital role in shaping the future of these industries [10,17].

Machine learning for predictive modeling

Machine learning has emerged as a powerful tool for predicting the behaviour of complex biological systems. The technology is particularly useful in analyzing large amounts of data and identifying patterns and relationships that would be difficult for human researchers to detect. Using machine learning, researchers have developed neural networks that can predict the circular patterns that would be created by a biological circuit embedded into a bacterial colony. In fact, the system works 30,000 times faster than the existing computational model, enabling rapid construction and evaluation of engineered pathways. These predictions can be used to guide the design and engineering process in several ways. Firstly, machine learning can optimize experimental designs, pinpoint and enhance metabolic pathways for generating specific compounds, and design custom genetic circuits for various industrial applications. Secondly, machine learning can predict the impact of bioengineering approaches on the host and the environment, which can help achieve the goal of engineering cells to a specification. The potential of machine learning to drive innovation and address critical challenges is demonstrated by successful applications of the technology in areas such as biofuel production, drug discovery, and environmental remediation. By providing a faster and more accurate way to analyze complex biological systems, machine learning can help researchers expedite the development of novel biological systems and address pressing challenges in medicine, manufacturing, and agriculture [18].

Machine learning has emerged as a powerful tool in predicting complex biological phenomena, from predicting protein structures to understanding cellular responses and organismal phenotypes. One of the most significant applications of machine learning in biology is in protein structure prediction. AlphaFold, a machine learning system developed by DeepMind, has shown remarkable accuracy in predicting protein structures based on amino acid sequences, which can have broad implications for drug discovery and understanding protein function [19-21]. Another successful application of machine learning in biology is in predicting cellular responses. Researchers have developed machine-learning models that accurately predict cellular behaviour in response to changes in electric fields in multiple cell types. This model can capture stochastic cell responses, allowing for the prediction of cellular behaviour in response to environmental changes. Machine learning methods have also been used to predict organismal phenotypes, such as the physical characteristics of yeast, rice, and wheat. These methods evaluate the potential of machine learning in predicting the physical characteristics of organisms from genotype and environmental information.

These examples illustrate the diverse applications of machine learning in predicting complex biological phenomena, ranging from the molecular scale to organismal behaviour. With the growing amount of biological data being generated, machine learning is likely to continue to play a significant role in advancing our understanding of the natural world.

AI-driven automation and control

AI automates tasks in synthetic biology labs, such as DNA assembly, protein expression, and cell culture optimization: Advances in Artificial Intelligence (AI) have enabled the automation of many tasks in synthetic biology labs, such as DNA assembly, protein expression, and cell culture optimization. More recently, researchers have been developing closed-loop systems that integrate real-time monitoring and AI for the precise control of biological processes [22-24].

One of the most promising applications of closed-loop systems is in personalized drug delivery. By analyzing patient-specific data, AI algorithms can adjust drug release rates to provide adaptive therapy that is tailored to the individual's needs. Wearable devices and sensors provide continuous data, and AI makes informed decisions about drug dosage and release rates, creating a feedback loop for precise, personalized drug administration [25].

In healthcare, closed-loop systems that incorporate AI, the Internet of Things (IoT), and health monitoring sensors allow for real-time monitoring, data collection, online analysis, diagnosis, and treatment recommendations. These systems have the potential to revolutionize healthcare, enabling personalized and responsive treatment that can improve patient outcomes and reduce costs [26].

In animal health, AI-based analytics are being used to monitor animals in real time, improving animal welfare and enabling preventative measures and individualized treatment. For example, farmers can use sensors to monitor the health of their livestock and AI algorithms to detect early signs of disease or distress [27].

Overall, closed-loop systems that integrate real-time monitoring and AI have the potential to transform a wide range of domains, from personalized medicine to animal health monitoring. As AI continues to evolve and become more sophisticated, we can expect to see even more applications of closed-loop systems in the future.

AI has proven to be a powerful tool in a variety of fields, including high-throughput screening and biomanufacturing. In the context of high-throughput screening, AI has enabled the development of deep learning frameworks that enhance the understanding of mechanism-driven drug action and enable drug repurposing for diseases such as COVID-19. This has been achieved through the use of AI-driven iterative screening, which has been shown to improve hit finding, offering significant boosts in screening efficacy and enabling the selection of the most promising compounds from large libraries based on machine learning predictions [28-30].

In biomanufacturing, AI and machine learning have been applied to overcome challenges in continuous-mode production, where the integration of AI into continuous fermentation processes has enabled the identification of critical factors impacting performance. This has allowed for the application of real-time feedback control to maintain process reliability with timely adjustments and controls for variations or fluctuations. Additionally, AI has the potential to solve engineering design problems in biomanufacturing, enhancing efficiency, productivity, and innovation. The example above demonstrates how AI is being used in a range of applications, from drug discovery to process optimization, and how it is helping to drive innovation in high-throughput screening and biomanufacturing [31-32].

Potential risks associated with the use of Artificial Intelligence (AI)

Artificial Intelligence (AI) has advanced biotechnology but has also created potential risks. These risks raise concerns about biosecurity, safety, and regulation. The discussion section of a research paper can include detailed content that sheds light on the risks associated with AI-designed bioweapons and gene manipulation for environmental impact.

AI-designed bioweapons and biosecurity

AI-designed proteins used for bioweapons present a threat to biosecurity if not regulated and monitored. Genetic engineering and synthetic biology have resulted in next-generation bioweapons that are lethal, reliable, and resistant to existing treatments [33]. Also, tailor-made microorganisms such as bioweapons are now possible, raising serious threats to peace and security due to their capacity for mass destruction [34,35].

Gene manipulation and technological advances

New technologies like gene editing, particularly CRISPR/Cas systems [36], have lowered barriers to developing bioweapons. This ease of genetic manipulation allows relatively harmless biological agents to be transformed into more dangerous ones. The integration of AI in genetic manipulation has increased accessibility to potentially harmful technologies for both state and non-state actors, raising concerns about misuse and biosecurity risks.

International cooperation and regulation

To address the risks associated with AI-designed bioweapons and gene manipulation for environmental impact, effective regulation, monitoring, and international cooperation are paramount. Effective regulatory frameworks are necessary to bridge gaps in existing policies and regulations due to the convergence of AI and life sciences in bioweapons development. These frameworks can mitigate the risk of global biological catastrophes.

Biodisaster X and environmental impact

The concept of "Biodisaster X" highlights the looming risk from biotechnologies, emphasizing the need for technology-based solutions, including AI and advanced communication technologies like 6G, to prevent and control potential biodisasters. The risks extend beyond bioweapons to gene manipulation for environmental impact, with AI and biotechnologies posing threats to lives, livelihoods, and economies on a global scale [35].

In conclusion, comprehensive governance, international collaboration, and responsible AI development are necessary to mitigate the risks associated with AI-designed bioweapons and gene manipulation for environmental impact.

Challenges

Synthetic biology is a rapidly expanding field that involves the development of biological systems for various applications, such as the production of biofuels or the development of new drugs. However, the complexity and insufficiently understood nature of biological systems pose significant data limitations to the field. While advancements have improved the predictability of synthetic biology systems, there are still areas where information is unknown, which can limit the application of AI techniques. Another challenge in using AI in synthetic biology is interpretability. AI models often employ "black boxes," making it difficult to understand the reasoning behind their predictions. This lack of interpretability may hinder the ability of researchers to design and engineer biological systems, as it can be challenging to troubleshoot and optimize the performance of these systems. Furthermore, the adoption of impactful AI applications in synthetic biology may pose several obstacles. The complexity of existing lab processes and the need for large benefits to overcome adoption costs are two significant barriers. Additionally, the proprietary nature of some aspects of organism engineering and closed systems can hinder the integration of AI and automation. This may limit the ability of researchers to collaborate and innovate, which could slow down progress in the field.

Ethical considerations

The application of AI in synthetic biology is an area of research that presents both opportunities and challenges. One major issue is related to biosafety and biosecurity, as AI has the potential to automate and optimize biological processes, which could result in chance consequences. For instance, the release of genetically modified organisms into the environment could have adverse effects on ecosystems and human health. Therefore, it is crucial to establish robust biosafety measures to prevent such occurrences. These measures may include implementing containment strategies, conducting risk assessments, and adhering to strict regulations and guidelines to ensure the safe and ethical use of AI in synthetic biology.

Future prospects

The integration of AI in synthetic biology presents both challenges and opportunities. On one hand, AI can greatly revolutionize various fields, including medicine, manufacturing, and agriculture by automating tasks, optimizing experimental designs, and predicting biological behaviours. This can expedite the development of novel biological systems and address pressing global challenges. On the other hand, there are challenges related to data, interpretability, and ethical considerations that need to be addressed.

One of the primary challenges is related to data. AI requires large amounts of data to train models and make accurate predictions. However, obtaining high-quality and representative data sets can be difficult, especially in the field of synthetic biology where data is often limited. Additionally, the interpretability of AI-generated results is another challenge. Understanding the reasoning behind AI-generated predictions can be challenging, which can make it difficult to validate results and identify potential errors or biases. Lastly, ethical considerations are also important to consider. The use of AI in synthetic biology can raise concerns related to safety, privacy, and equitable access to technology. Therefore, close collaboration between practitioners of both disciplines is essential to realizing the potential benefits of integrating AI techniques in synthetic biology. By addressing these challenges and developing robust ethical and safety frameworks, we can fully realize the potential of AI in synthetic biology and drive innovation to address critical global challenges.

Conclusion

The integration of Artificial Intelligence (AI) with Synthetic Biology has the potential to transform numerous fields, including medicine, agriculture, and manufacturing. The efficiency and accuracy offered by AI can automate tasks, optimize experimental designs, and predict biological behaviours, enabling researchers to design and engineer biological systems more efficiently. However, there are several challenges related to data limitations, interpretability issues, and ethical considerations such as biosafety and biosecurity concerns that pose significant challenges. It is essential to develop responsible frameworks for the development and application of AI in synthetic biology, considering the potential risks and benefits of these technologies. Despite these challenges, successful applications of AI in areas like high-throughput screening and biomanufacturing demonstrate the potential of these technologies to drive innovation and address critical challenges. AI can analyze vast amounts of data and identify patterns that would be impossible for humans to detect, allowing researchers to accelerate the pace of scientific discovery. Moreover, the development of AI-powered closed-loop systems for real-time monitoring and control of biological processes is another promising area. These systems can provide researchers with real-time feedback on the performance of biological systems and enable them to optimize these systems on the fly. The future prospects of AI in synthetic biology are vast, and its potential to transform various fields is immense. However, it is crucial to address the challenges and ethical considerations associated with the development and application of these technologies. By doing so, we can leverage the power of AI to drive innovation and solve some of the most pressing challenges facing society today.

References

1. Benner SA, Sismour AM. Synthetic biology. Nat Rev Genet. 2005

Jul;6(7):533-43. doi: 10.1038/nrg1637. PMID: 15995697; PMCID: PMC7097405.

2. Parthiban S, Vijeesh T, Gayathri T, Shanmugaraj B, Sharma A, Sathishkumar R. Artificial intelligence-driven systems engineering for next-generation plant-derived biopharmaceuticals. Front Plant Sci. 2023 Nov 15; 14:1252166. doi: 10.3389/fpls.2023.1252166. PMID: 38034587; PMCID: PMC10684705.

3. Garner KL. Principles of synthetic biology. Essays Biochem. 2021 Nov 2;65(5):791-811. doi: 10.1042/EBC20200059. PMID: 34693448; PMCID: PMC8578974.

4. Ran FA, Hsu PD, Wright J, Agarwala V, Scott DA, Zhang F. Genome engineering using the CRISPR-Cas9 system. Nat Protoc. 2013 Nov;8(11):2281-2308. doi: 10.1038/nprot.2013.143. Epub 2013 Oct 24. PMID: 24157548; PMCID: PMC3969860.

5. Redman M, King A, Watson C, King D. What is CRISPR/Cas9? Arch Dis Child Educ Pract Ed. 2016 Aug;101(4):213-5. doi: 10.1136/archdischild-2016-310459. Epub 2016 Apr 8. PMID: 27059283; PMCID: PMC4975809.

6. Bhardwaj A, Kishore S, Pandey DK. Artificial Intelligence in Biological Sciences. Life (Basel). 2022 Sep 14;12(9):1430. doi: 10.3390/life12091430. PMID: 36143468; PMCID: PMC9505413.

7. Eslami M, Adler A, Caceres RS, Dunn JG, Kelley-Loughnane N, Varaljay VA, Martin GH. Artificial Intelligence for Synthetic Biology. Communications of the ACM. 2022; 65(5):88-97. https://doi.org/10.1145/3500922

8. Helmy M, Smith D, Selvarajoo K. Systems biology approaches integrated with artificial intelligence for optimized metabolic engineering. Metab Eng Commun. 2020 Dec; 11:e00149. doi: 10.1016/j.mec.2020.e00149. Epub 2020 Oct 9. Erratum in: Metab Eng Commun. 2021 Oct 28;13:e00186. PMID: 33072513; PMCID: PMC7546651.

9. García Martín H, Mazurenko S, Zhao H. Special Issue on Artificial Intelligence for Synthetic Biology. ACS Synth Biol. 2024 Feb 16;13(2):408-410. doi: 10.1021/acssynbio.3c00760. Epub 2024 Jan 12. PMID: 38214972.

10. Liu Z, Wang J, Nielsen J. Yeast synthetic biology advances biofuel production. Curr Opin Microbiol. 2022 Feb; 65:33-39. doi: 10.1016/j.mib.2021.10.010. Epub 2021 Oct 29. PMID: 34739924.

11. Merzbacher C, Oyarzún DA. Applications of artificial intelligence and machine learning in dynamic pathway engineering. Biochem Soc Trans. 2023 Oct 31;51(5):1871-1879. doi: 10.1042/BST20221542. PMID: 37656433; PMCID: PMC10657174.

12. Cheng Y, Bi X, Xu Y, Liu Y, Li J, Du G, Lv X, Liu L. Machine learning for metabolic pathway optimization: A review. Comput Struct Biotechnol J. 2023 Mar 27;21: 2381-2393. doi: 10.1016/j.csbj.2023.03.045. PMID: 38213889; PMCID: PMC10781721.

13. García-Granados R, Lerma-Escalera JA, Morones-Ramírez JR. Metabolic Engineering and Synthetic Biology: Synergies, Future, and Challenges. Front Bioeng Biotechnol. 2019 Mar 4;7: 36. doi: 10.3389/fbioe.2019.00036. PMID: 30886847; PMCID: PMC6409320.

14. Popescu SM, Mansoor S, Wani OA, Kumar SS, Sharma V, Sharma A, Arya VM, Kirkham MB, Hou D, Bolan N, Chung YS. Artificial intelligence and IoT driven technologies for environmental pollution monitoring and management. Frontiers in Environmental Science. 2024; 12(1336088). https://doi.org/10.3389/fenvs.2024.1336088

15. Ibn-Mohammed T, Mustapha KB, Abdulkareem M, Fuensanta UA, Pecunia V, Dancer CEJ. Toward artificial intelligence and machine learning-enabled frameworks for improved predictions of lifecycle environmental impacts of functional materials and devices. MRS Communications. 2023; 13:795–811. https://doi.org/10.1557/s43579-023-00480-w

16. Koyamparambath A, Adibi N, Szablewski C, Adibi SA, Sonnemann G. Implementing Artificial Intelligence Techniques to Predict Environmental Impacts: Case of Construction Products. Sustainability. 2022; 14(6):3699. https://doi.org/10.3390/su14063699

17. Long B, Fischer B, Zeng Y, Amerigian Z, Li Q, Bryant H, Li M, Dai SY, Yuan JS. Machine learning-informed and synthetic biology-enabled semi-continuous algal cultivation to unleash renewable fuel productivity. Nat Commun. 2022 Jan 27;13(1):541. doi: 10.1038/s41467-021-27665-y. PMID: 35087023; PMCID: PMC8795378.

18. Shaikhina T, Lowe D, Daga S, Briggs D, Higgins R, Khovanova N. Machine Learning for Predictive Modelling based on Small Data in Biomedical Engineering. IFAC-PapersOnLine. 2015; 48(20):469-474. https://doi.org/10.1016/j.ifacol.2015.10.185

19. Jumper J, Evans R, Pritzel A, Green T, Figurnov M, Ronneberger O, Tunyasuvunakool K, Bates R, Žídek A, Potapenko A, Bridgland A, Meyer C, Kohl SAA, Ballard AJ, Cowie A, Romera-Paredes B, Nikolov S, Jain R, Adler J, Back T, Petersen S, Reiman D, Clancy E, Zielinski M, Steinegger M, Pacholska M, Berghammer T, Bodenstein S, Silver D, Vinyals O, Senior AW, Kavukcuoglu K, Kohli P, Hassabis D. Highly accurate protein structure prediction with AlphaFold. Nature. 2021 Aug;596(7873):583-589. doi: 10.1038/s41586-021-03819-2. Epub 2021 Jul 15. PMID: 34265844; PMCID: PMC8371605.

20. Marcu ŞB, Tăbîrcă S, Tangney M. An Overview of Alphafold's Breakthrough. Front Artif Intell. 2022 Jun 9; 5:875587. doi: 10.3389/frai.2022.875587. PMID: 35757294; PMCID: PMC9218062.

21. Varadi M, Bertoni D, Magana P, Paramval U, Pidruchna I, Radhakrishnan M, Tsenkov M, Nair S, Mirdita M, Yeo J, Kovalevskiy O, Tunyasuvunakool K, Laydon A, Žídek A, Tomlinson H, Hariharan D, Abrahamson J, Green T, Jumper J, Birney E, Steinegger M, Hassabis D, Velankar S. AlphaFold Protein Structure Database in 2024: providing structure coverage for over 214 million protein sequences. Nucleic Acids Res. 2024 Jan 5;52(D1):D368-D375. doi: 10.1093/nar/gkad1011. PMID: 37933859; PMCID: PMC10767828.

22. Jafari M, Marquez G, Dechiraju H, Gomez M, Rolandi M. Merging machine learning and bioelectronics for closed-loop control of biological systems and homeostasis. Cell Reports Physical Science. 2023; 4(8):101535.

23. Schöning J, Pfisterer HJ. Safe and Trustful AI for Closed-Loop Control Systems. Electronics. 2023; 12(16):3489. https://doi.org/10.3390/electronics12163489

24. Jin X, Cai A, Xu T, Zhang X. Artificial intelligence biosensors for continuous glucose monitoring. Interdisciplinary Materials, Review. 2023. https://doi.org/10.1002/idm2.12069

25. Vidhya KS, Sultana A, M NK, Rangareddy H. Artificial Intelligence's Impact on Drug Discovery and Development from Bench to Bedside. Cureus. 2023 Oct 22;15(10):e47486. doi: 10.7759/cureus.47486. PMID: 37881323; PMCID: PMC10597591.

26. Stead WW, Patel NR, Starmer JM. Closing the loop in practice to assure the desired performance. Trans Am Clin Climatol Assoc. 2008; 119:185-94; discussion 194-5. PMID: 18596845; PMCID: PMC2394683.

27. AlZubi AA. Artificial Intelligence and its Application in the Prediction and Diagnosis of Animal Diseases: A Review. Indian Journal of Animal Research. 2023; 57(10):1265-1271. https://doi.org/10.18805/IJAR.BF-1684

28. Kwon KK, Lee J, Kim H, Lee DH, Lee SG. Advancing high-throughput screening systems for synthetic biology and biofoundry. Current Opinion in Systems Biology. 2024; 37:100487. https://doi.org/10.1016/j.coisb.2023.100487

29. Beardall WAV, Stan GB, Dunlop MJ. Deep Learning Concepts and Applications for Synthetic Biology. GEN Biotechnol. 2022 Aug 1;1(4):360-371. doi: 10.1089/genbio.2022.0017. Epub 2022 Aug 18. PMID: 36061221; PMCID: PMC9428732.

30. Amore A, Philip S. Artificial intelligence in food biotechnology: trends and perspectives. Frontiers in Industrial Microbiology. 2023; 1:1255505. https://doi.org/10.3389/finmi.2023.1255505

31. Holzinger A, Keiblinger K, Holub P, Zatloukal K, Müller H. AI for life: Trends in artificial intelligence for biotechnology. N Biotechnol. 2023 May 25;74:16-24. doi: 10.1016/j.nbt.2023.02.001. Epub 2023 Feb 6. PMID: 36754147.

32. Sharma A, Gupta G, Ahmad T, Krishan K, Kaur B. Next generation agents (synthetic agents): Emerging threats and challenges in detection,

protection, and decontamination. Handbook on Biological Warfare Preparedness. 2020; 217–56. doi: 10.1016/B978-0-12-812026-2.00012-8. Epub 2019 Oct 11. PMCID: PMC7153315.

33. Christopher MA, LucasC, Guest E. The Operational Risks of AI in Large-Scale Biological Attacks: A Red-Team Approach. Santa Monica, CA: RAND Corporation. 2023. https://www.rand.org/pubs/research_reports/RRA2977-1.html.

34. van Aken J, Hammond E. Genetic engineering and biological weapons. New technologies, desires and threats from biological research. EMBO Rep. 2003 Jun;4 Spec No(Suppl 1):S57-60. doi: 10.1038/sj.embor.embor860. PMID: 12789409; PMCID: PMC1326447.

35. Nidhi S, Anand U, Oleksak P, Tripathi P, Lal JA, Thomas G, Kuca K, Tripathi V. Novel CRISPR-Cas Systems: An Updated Review of the Current Achievements, Applications, and Future Research Perspectives. Int J Mol Sci. 2021 Mar 24;22(7):3327. doi: 10.3390/ijms22073327. PMID: 33805113; PMCID: PMC8036902.

36. Su Z, McDonnell D, Bentley BL, He J, Shi F, Cheshmehzangi A, Ahmad J, Jia P. Addressing Biodisaster X Threats with Artificial Intelligence and 6G Technologies: Literature Review and Critical Insights. J Med Internet Res. 2021 May 25;23(5):e26109. doi: 10.2196/26109. PMID: 33961583; PMCID: PMC8153034.