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A New Era of Discovery: How Artificial Intelligence has Revolutionized the Biotechnology

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Abstract

In the growing field of biotechnology, artificial intelligence (AI) has emerged as a pivotal force of innovation, unveiling a new era of discovery and advancement. The convergence of AI with biotechnology has revolutionized the landscape of scientific research and development. The dynamic interplay between AI and biotechnology highlights the transformative power of AI techniques in accelerating advancements in drug discovery, development, personalized medicine, biomolecular engineering, bioprocessing, CRISPR technology, genome editing, genomics, proteomics, metabolomics, transcriptomic, and AI-enabled robotics in biotechnology. This integration of AI with biotechnology helps us combat global challenges and offers environmentally friendly and sustainable solutions like bioremediation, bioplastics, biodiesel, and biofiltration. Current examples of these problems include waste management, air pollution, healthcare, clean water, energy access, sustainable practices, conservation of biodiversity, and ecosystems. This review article provides a comprehensive analysis, drawing on current literature, case studies, and emerging trends, to highlight the transformative potential of AI in reshaping the biotechnological landscape. It also addresses the challenges and opportunities associated with this AI-powered transformation, discussing future directions, ethical considerations, and the need for human-AI collaboration to ensure responsible and sustainable progress for a brighter future.

Key words: Artificial Intelligence, Biotechnology, Biological Sciences, Scientific research, Machine learning

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Introduction

Various industries are feeling the impact of artificial intelligence (AI), which is rapidly transforming the world around us. It sets the pace for a wave of transformation that is reshaping industries, redefining the boundaries of creativity, and revolutionizing scientific inquiry. The incredible potential of artificial intelligence (AI) to solve complex problems and drive innovation is due to its ability to process huge amounts of data, detect patterns, and make predictions with a high degree of accuracy [1]. At the Dartmouth Conference in 1956, John McCarthy used the phrase "artificial intelligence (AI)" for the first time to refer to an intelligent machine system [2]. Driven by algorithms, AI is excellent at analyzing data, recognizing patterns, and predicting future outcomes. Some of these algorithms can be based on logic, rules, or artificial neural networks that approximate the way the human brain works. Analyzing large datasets, automating tasks, and finding hidden patterns that people could possibly miss are among the ways in which artificial intelligence helps. This can speed up the process of research, lead to new discoveries, and make scientific investigations more effective. AI has now found its niche in biology by applying creative, leading-edge strategies [3].

Historically, biotechnology has been characterized by systematic laboratory experiments, tedious data manipulation, and reliance on human instinct. Nonetheless, AI technology appears to be opening a fresh domain where machines can augment human abilities and derive innovative insights from vast amounts of intricate information [4]. This article examines the multifaceted impact of AI on biotechnology, with a particular focus on its various techniques and fields. In the field of biotechnology, artificial intelligence (AI) has modernized drug discovery and development approaches as well as personalized medicine practices, bio-molecular engineering and design, bioprocessing and manufacturing, and genome editing methods, including CRISPR technology, among others [5]. AI can provide support in discovering novel therapeutic objectives, generating individualized treatment schedules, and enhancing bioprocesses for sustainability and efficiency based on genetic and clinical data [6]. AI's capability to analyze large-scale data generated from genomics, proteomics, transcriptomes, and metabolomics revolutionizes the conventional methods and approaches used in biotechnology [7].

AI's transformative impact has been widely acknowledged, with its ability to enhance accuracy and productivity driving advancements across diverse sectors of biotechnology. The influence of AI extends to healthcare as well, playing a pivotal role in drug development and enabling personalized medicine. In agriculture and food science, AI is revolutionizing crop production and refining food processing methods. The incorporation of AI into environmental and marine biotechnology promotes creative approaches to biodiversity preservation and pollution mitigation, underscoring its essential contribution to the progress of scientific knowledge and real-world biotechnological advancements. This powerful alliance between AI and biotechnology is not only accelerating scientific discovery but also holds immense potential for addressing global challenges like waste management, healthcare advancement, environmental protection, and sustainable food production [8]. This review also looks at environmentally friendly ways to address these difficult problems by generating renewable energy, detoxifying heavy metals through bioremediation, utilizing biofiltration, creating biodiesel and bioplastics, developing biofuels, and enhancing plant resilience with the help of AI. However, what are the possible uses of AI in biotechnology in the future that could greatly help with global issues?

Although biotechnology has greatly benefited from artificial intelligence (AI), which has brought previously unheard-of precision and efficiency, AI still confronts a number of obstacles, including the need for reliable algorithms that can predict complicated biological consequences, data privacy, and ethical concerns in genetic editing. The three main directions for the future are the establishment of transparent, ethical AI guidelines, interdisciplinary collaboration between biotechnology and AI to enhance their use in addressing global problems, and finally the deployment of AI in combating health issues. However, when dealing with issues such as data security, openness, and socio-economic implications, there is a need to exercise caution while implementing AI in biotechnology. The objective of this review paper is to investigate, evaluate, and summarize the present situation regarding this revolutionary collaboration between biotechnology and artificial intelligence.

How AI has revolutionized the Biotechnological Products and Methods?

Artificial intelligence (AI) has a significant and groundbreaking impact on biotechnology, updating conventional methods and opening up new avenues for scientific investigation, medical and wellness research, and industrial applications [9]. By merging advanced computing with the biological sciences, researchers are achieving previously unimaginable progress. AI and machine learning (ML) have significantly impacted traditional biotechnological methods across various areas. Here are key areas where AI has made a significant impact across biotechnology:

Drug Discovery and Development

Artificial intelligence (AI) has transformed the pharmaceutical industry in numerous ways. AI can be used in pharmaceuticals for anything from product management to medication development [10]. However, the lack of cutting-edge technologies hinders the medication development process, making it a costly and time-consuming undertaking that can be resolved with AI [11]. Artificial intelligence (AI) has the ability to identify hit and lead compounds, expedite the confirmation of the drug target, and optimize the design of the drug structure [12]. Several AI tools are being used and explored in different stages of drug discovery and development, each contributing unique strengths. Machine learning algorithms learn from existing data to identify patterns and make predictions. These algorithms are used for various tasks in drug discovery [13], including virtual screening: identifying promising drug candidates from large databases of molecules [14] and toxicity prediction: assessing safety risks of potential drugs [15]. XGBoost [16] and Random Forest (classification and regression) are a few example [17]. Deep learning is promoting a scientific revolution fueled by huge data, accessible toolkits, and powerful computational resources, touching many domains, including protein structural modeling [18] and high-dimensional data, such as genomic data: identifying potential drug targets based on gene function and disease association and protein structure data: designing and simulating potential drug molecules that can interact with specific targets. In the realm of drug discovery, the primary deep learning frameworks that are commonly employed include convolutional neural networks [CNN], recurrent neural networks [RNN], and generative deep neural networks [GDNN] [19]. Other examples are Alpha fold (protein structure prediction) [20], DeepChem (molecular property prediction and drug design) [21].

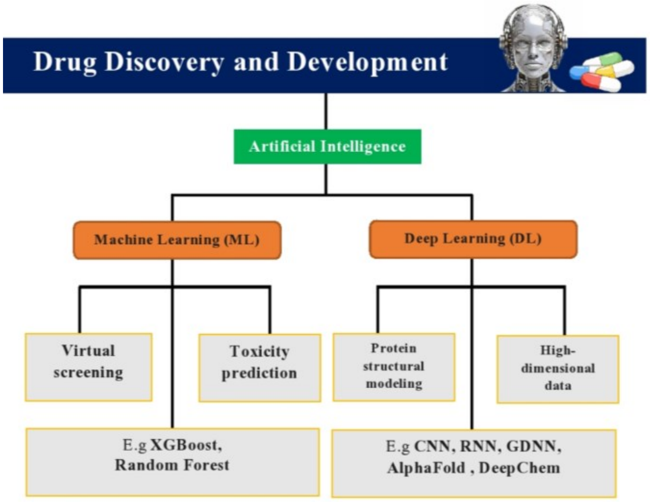

Figure 1. AI-powered tools and techniques in drug discovery and development

Personalized Medicine

AI has a significant potential to advance the creation of personalized medications. AI may evaluate a person's genetic information as well as other forms of health data to create individualized treatment strategies that are tailored to their unique requirements. [22]. This includes identifying possible negative reactions and predicting an individual's response to a certain treatment using machine learning algorithms. To improve disease detection, treatment, and medication administration with precision and accuracy, personalized medicine must be established or built using AI approaches [23]. Numerous AI algorithms are applied in the medical domain, particularly in the area of personalized medicine [23]. Personalized medicine can greatly benefit from artificial neural networks, which have the potential to provide more accurate diagnoses, efficient therapies, and ultimately better patient care [24]. Several studies demonstrate that by evaluating diagnostic criteria and spectral data, ANN can reliably diagnose various diseases, such as malignant melanoma, eye issues, and various types of cancer [23]. Through the analysis of various datasets, such as genetic data, patient histories, and lifestyle factors, artificial intelligence [AI) enables personalized treatment. This enables medical professionals to customize care for each patient, optimizing therapeutic outcomes, maximizing positive effects, and reducing negative ones [25].

Bio-molecular Engineering and Design

Developing and modifying biomolecules such as proteins, enzymes, nucleic acids, and lipids—to carry out certain tasks is known as biomolecular engineering. These modified biomolecules are employed in biotechnology for a number of purposes, such as medication delivery, gene therapy, biocatalysts, and the creation of biomaterials [26]. AI, specifically machine learning and automation technologies, has completely transformed the field of molecular engineering and design by providing advanced tools for analyzing intricate biological information, simulating molecular interactions, and expediting the design process, beyond the capabilities of traditional computational software and databases such as protein data banks and NCBI databases [27]. Here are some AI tools and methods commonly employed in molecular engineering and design. In the realm of protein structure prediction, drug discovery and enzyme engineering, machine learning plays a role by extracting insights, from large datasets [28]. Alpha fold stands as a dominant tool for predicting protein structures [20]. Deep learning a branch of machine learning that specializes in the analysis of intricate biological data, such as molecular dynamics and protein-protein interactions. Large chemical libraries and biological data can be analyzed by deep learning algorithms to find potential drug candidates that target particular disorders [29]. Generative Adversarial Networks (GANs) are a subfield of deep learning techniques that can be utilized to produce new biomolecules with desired properties. This is a cutting-edge method that could completely change biomolecular engineering and design [30]. Docking Simulations can anticipate binding affinity and guide drug design by simulating the interactions between tiny molecules (drugs) and target macromolecules (proteins) [31]. An essential technique for computer-aided drug development is docking simulation [32].

Bioprocessing and Manufacturing

AI increases the efficiency of bioprocessing and production in industrial biotechnology [33]. Algorithms like automation and machine learning improve fermentation processes [34], keep an eye on bioreactors [35], and expand the production of bio-based goods [36]. AI technologies and approaches are bringing about a major revolution in bioprocessing and manufacturing. Machine learning (ML) analyzes sensor data from equipment and bioreactors to analyze and predict potential failures and schedule maintenance proactively, minimizing downtime and guaranteeing process efficiency [37]. By using past bioprocessing data, machine learning algorithms can determine the ideal values for variables like pH, temperature, and nutrient concentrations, which improves product production and quality [38]. In order to optimize process conditions and ensure product consistency, deep learning algorithms can evaluate complicated bioprocess data in real-time and provide feedback for automated control systems [33]. Robotics and automation can be used to program robots for tasks like aseptic handling, sample preparation, and packing, boosting efficiency, safety, and decreasing human error in bio manufacturing [39]. AI presents a major possibility for changing bioprocessing and manufacturing. By solving problems and fostering collaboration, AI can lead to more efficient, robust, and cost-effective bio manufacturing processes, ultimately boosting the manufacture of life-saving medications, therapies, and other bioproduct.

Genomics

The study of genomes, or an organism's entire collection of DNA, is known as genomics [40]. This is directly relevant to biotechnology as it enables gene therapy, genetic engineering [41], and the creation of genetically modified organisms (GMOs) for agricultural applications. The accuracy and speed of genome sequencing and annotation have increased with the help of AI techniques, especially machine learning algorithms. [42]. They support the understanding of gene expression patterns, gene function prediction, and the identification of genetic variants associated with disease. Analysis of genomic variations is done using Deep Variant [43].

Proteomics and Protein Structure Prediction

Proteomics, which involves the comprehensive analysis of all the proteins synthesized by an organism, is important for comprehending disease mechanisms, finding therapeutic targets, and developing protein-based drugs [44]. Proteomics uses deep learning methods, including convolutional neural networks (CNNs) for protein structure prediction [45], functional annotation, and protein-protein interaction detection. This quickens the process of discovering new drugs and developing innovative diagnostics. Artificial intelligence plays a crucial role in forecasting protein structures, which is essential for comprehending biological functions [27].

Transcriptomic and Gene Expression Analysis

Transcriptomic is dedicated to analyzing the transcriptome, which encompasses all RNA transcripts generated by the genome [46]. AI has transformed the field of transcriptomes by facilitating the examination of extensive RNA-seq data, forecasting RNA structures, and comprehending the regulatory mechanisms governing gene expression [47]. This advances the fields of functional genomics and personalized medicine. AI technologies facilitate accurate analysis of transcriptomic data, unveiling gene expression patterns and regulatory networks [48]. This improves our comprehension of cellular mechanisms, specializations, and reactions to environmental stimuli. SignatraX leverages gene expression data acquired from RNA sequencing experiments to identify genes that are crucial in disease processes. These identified genes hold the potential to become drug targets for therapeutic intervention. Additionally, SignatraX can be employed in the identification of drug targets [49].

Metabolomics and Metabolic Pathway Optimization

Metabolomics is the study of small-molecule metabolites found within cells, tissues, or organisms [50], plays a key role in detecting biomarkers for disease, comprehending metabolic pathways, and refining crop engineering. Artificial intelligence enables the examination of metabolomics data, assisting in the detection of metabolites and the enhancement of metabolic pathways [51]. AI and machine learning models play a crucial role in the field of metabolomics by analyzing intricate metabolic data, discovering novel metabolites, and unraveling metabolic pathways [52]. This enhances our understanding of organism’s responses to different biological conditions. This is crucial in metabolic engineering for the production of biofuels, pharmaceuticals, and other high-value compounds.

CRISPR Technology and Genome Editing

CRISPR, an acronym for "Clustered Regularly Interspaced Short Palindromic Repeats," has transformed the biotechnology industry as a powerful gene-editing instrument. CRISPR's ability to edit genes with high accuracy and efficiency makes it a game-changer in biotechnology. AI tools enhance the precision and efficiency of CRISPR-based genome editing [53]. Machine learning algorithms predict off-target effects, guide RNA design, and optimize the outcomes of genome editing experiments. Traditionally, designing guide RNAs, the molecules that target specific locations in DNA for editing, was a time-consuming and laborious process. AI algorithms can now analyze vast genetic datasets to predict highly effective guide RNA sequences with greater accuracy [54]. This saves researchers time and effort and increases the success rate of targeted gene editing. One concern with CRISPR is the possibility of unintended edits (off-target effects) at locations other than the targeted DNA sequence.

Table 1. AI-powered tools and techniques that enhanced biotechnological methods

SN	Machine Learning	Function	Application in Biotechnology	Reference
1.	XGBoost	Efficient Prediction	Drug Discovery and Development	[16]
2.	Random Forest	Pattern Recognition	Drug Discovery and Development	[17]
3.	Artificial Neural Network	Precise Diagnoses	Personalized Medicine	[23]
4.	SignatraX	Drug Target Identification	Transcriptomic	[49]
5.	CRISPR-P	Design High-fidelity guide RNAs	CRISPR Technology	[55]
	Deep Learning			
6.	Generative Deep Neural Networks [GDNN]	Molecule Design	Drug Design	[19]
7.	Alpha Fold	Protein Structure Prediction	Drug Discovery and Development	[20]
8.	Deep Chem	Molecular Property Prediction	Drug Design	[21]
9.	Soft Sensors	Estimate Bioprocess Parameters	Bioprocessing	[58]
10.	Deep Variant	Genomic Variation Analysis	Genomics	[43]
11.	Convolutional Neural Networks [CNN]	Protein Structure Prediction	Proteomics	[45]
12.	DeepCpfR	Predicting off-target effects of guide RNA sequences	CRISPR Technology	[56]
13.	Docking Simulations	Computer-aided Drug Discovery	Bio-molecular Engineering	[32]
14.	Lifecycle Analysis	Assess the Environmental Impacts	Bioplastics	[59]

AI can analyze a proposed guide RNA and predict potential off-target effects. This allows researchers to design more specific guide RNAs with minimal off-target risks, improving the safety and accuracy of CRISPR editing. CRISPR-P is an online platform that uses AI to design high-fidelity guide RNAs [55]. DeepCpfR is an AI tool for predicting off-target effects of guide RNA sequences [56].

AI-enabled Robotics in Biotechnology

Robotics, coupled with AI, finds applications in laboratory automation, sample handling, and high-throughput experimentation. This improves efficiency and reproducibility in biotechnological workflows. AI-enabled robotics is rapidly transforming the field of biotechnology, bringing increased efficiency, precision, and automation to various processes. Many laboratory tasks, like sample preparation, purification, and analysis, involved repetitive manual work. Robots can perform various tasks, including precise pipetting and sample handling for consistent and reproducible results, automated liquid handling protocols for tasks like DNA extraction and protein purification, integration with laboratory instruments for data collection and analysis. Robots can perform tasks with greater accuracy and consistency than human operators. Automation can streamline workflows and reduce the need for manual labor. Robotics minimizes human exposure to hazardous materials and reduces the risk of errors. AI can analyze large datasets from robotic experiments, leading to new discoveries and insights.

Powering Biotech's Future: A Look at AI Networks and Tools

AI encompasses a spectrum of methods, including reasoning, knowledge representation, and solution search, with machine learning (ML) standing as a core paradigm. Within ML, deep learning [DL) dives deeper, utilizing artificial neural networks [ANNs) that mirror the complexity of human neurons, capturing the essence of how our brains process and transmit information [57]. The following table highlights some key AI tools and techniques that are transforming the field of biotechnology.

Table 2: How AI has transformed numerous sectors within the field of biotechnology

Medical Biotechnology	Example	AI-based medical imaging for disease diagnosis
	AI Tools	Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs), Natural Language Processing (NLP)
	Future Prospects	Personalized medicine, drug discovery acceleration, precision diagnostics
Animal Biotechnology	Example	AI-driven breeding programs for livestock improvement
	AI Tools	Machine Learning models for genotype-phenotype prediction, Genetic Algorithms for optimization [60]
	Future Prospects	Disease-resistant animal breeds, enhanced productivity, conservation efforts
Plant Biotechnology	Example	AI-guided crop breeding and optimization for climate resilience
	AI Tools	Deep Learning for crop disease detection, Reinforcement Learning for optimizing crop growth conditions (61]
	Future Prospects	Climate-smart crops, increased crop yields, sustainable agriculture
Industrial Biotechnology	Example	AI-driven process optimization in bio manufacturing
	AI Tools	Reinforcement Learning for process optimization, Genetic Algorithms for strain engineering [62]
	Future Prospects	Enhanced bio production efficiency, greener manufacturing processes, novel bioproduct
Food Biotechnology	Example	AI-based food safety monitoring and quality control
	AI Tools	Machine Learning for food fraud detection, Deep Learning for food image analysis [63]
	Future Prospects	Improved food safety, personalized nutrition, sustainable food production
Health Biotechnology	Example	AI-driven predictive analytics for disease prevention and management
	AI Tools	Machine Learning for patient risk stratification, Natural Language Processing for electronic health record analysis
	Future Prospects	Precision health interventions, remote patient monitoring, early disease detection
Agriculture Biotechnology	Example	AI-enabled precision agriculture for optimized resource utilization
	AI Tools	IoT sensors and drones for data collection [64], Machine Learning for decision support systems
	Future Prospects	Sustainable farming practices, reduced environmental impact, increased food security
Environmental Biotechnology	Example	AI-driven pollution monitoring and remediation strategies
	AI Tools	Machine Learning for environmental data analysis, Reinforcement Learning for autonomous monitoring systems
	Future Prospects	Cleaner ecosystems, sustainable waste management, biodiversity conservation
Marine Biotechnology	Example	AI-guided marine resource exploration and conservation efforts
	AI Tools	Machine Learning for marine species identification, Deep Learning for oceanographic data analysis [65]
	Future Prospects	Sustainable fisheries management, marine biodiversity preservation, ocean health monitoring
Nano Biotechnology	Example	AI-driven drug delivery systems using nanoparticles
	AI Tools	Quantum Machine Learning for nanomaterial design, Deep Learning for nanoscale imaging [66]
	Future Prospects	Targeted drug delivery, nanosensors for disease detection, advanced biomaterials

The Expanding Universe of AI-Powered Biotechnology: A Look at 10 Key Industries

AI has revolutionized various branches of biotechnology, enabling advancements in medical, animal, plant, industrial, food, health, agriculture, environmental, marine, and Nanobiotechnology. It has brought about a significant revolution in the diverse realms of biotechnology. Within the realm of medical biotechnology, AI plays a pivotal role in driving revolutionary progress in personalized medicine and diagnostics. This makes it possible to develop treatments that are tailored to individuals' individual genetic profiles. This has led to the development of AI-based tools for genetic editing and breeding programs which have enhanced plant and animal biotechnology enabling better resistance against diseases, improved productivity and performance. In addition to this, AI is employed in industrial biotechnology where it helps in optimizing production processes as well as creating new materials. The use of AI-driven monitoring and management systems has greatly contributed towards advancements in environmental and agricultural biotechnologies by improving such aspects like resource optimization, crop yield maximization among others. Disease surveillance and public health strategies also benefit from predictive analytics used in health biotechnology through advanced AI techniques. Marine resources are managed with the help of artificial intelligence, thus contributing significantly towards marine biodiversity conservation ensuring sustainable utilization of these resources. Nano-biotechnology leverages on artificial intelligence [AI) for the improvement of drug delivery systems thereby transforming diagnostic architectures; hence enhancing precision medicine applications [3]. The influence of AI on various industries is evident through specific examples, tools, and methods employed, as well as the potential opportunities that lie ahead.

How AI with Biotechnology, empowering us to address Global Challenges?

Integrating AI with biotechnological tools and techniques amplifies the effectiveness and efficiency of solving global challenges and environmental problems. This synergy not only accelerates our response to these pressing issues but also opens new avenues for sustainable and innovative environmental management practices. There is how AI has helped out biotechnological methods in solving complex challenges.

Through the development of biofuels from algae or other biomass [67], biotechnology contributes to the creation of sustainable and renewable energy sources, reducing reliance on fossil fuels and decreasing carbon footprints. AI algorithms can optimize the growth conditions and processing of biofuel-producing organisms, increasing yield and reducing costs, making biofuels a more viable alternative to fossil fuels. Machine Learning (ML) predictive models used to forecast biofuel production from algae or biomass, optimizing harvesting times and processing conditions. Optimization algorithms fine-tune the parameters for biofuel production processes, maximizing yield and reducing resource consumption.

Certain bacteria and plants have the ability to accumulate and detoxify heavy metals from contaminated soils and water, making areas polluted with industrial waste safe again for wildlife and human use. AI models help to predict the effectiveness of certain microorganisms or plants in absorbing specific heavy metals, optimizing bioremediation strategies for contaminated sites. Deep learning for speciation analysis that predict how different heavy metals will interact with specific bioremediation agents, enhancing the efficacy of metal uptake or degradation. The Geographic Information System (GIS) integrated with AI for identifying and monitoring contaminated sites suitable for bioremediation [68].

One more example is given in the use of living materials like microbes and plants in bio filters to hold and degrade air pollutants biologically. The application of this technology is meant to control industrial emissions, hence reducing the level of harmful substances released into the atmosphere. AI also helps with optimizing the design and operations of biofiltration systems, determining combinations for specific pollutants, and maintaining good filtration efficiency by controlling parameters like airflow rate or humidity [69]. Bio filters are optimized by using simulation software that integrates AI in order to model airflow and pollutant degradation. Meanwhile, for microbial selection, machine learning is applied to determine the most successful consortiums capable of destroying any particular air pollutant.

Biotechnological processes can convert waste vegetable oils and animal fats into biodiesel [70], providing an environmentally friendly alternative to traditional fossil fuels. Artificial intelligence (AI) systems can optimize the chemical reactions that turn waste oils into biodiesel, increasing yield and efficiency while consuming less energy. Process optimization AI algorithms are utilized to optimize the chemical process parameters involved in the conversion of waste oils into biodiesel, thereby improving both the yield and quality of the final product. Machine learning models are utilized to forecast the quality of biodiesel derived from different feed stocks, guaranteeing adherence to fuel standards [71].

Genetic engineering and the use of CRISPR technology facilitate the advancement of crop cultivars that exhibit enhanced resilience against pests, diseases, and adverse climatic circumstances [72]. This reduces dependence on chemical pesticides and fertilizers, lowering agricultural runoff and enhancing ecosystem health. Machine learning methods allow faster analysis of genetic data to help identify which genes influence resistance to various types of stress. This speeds up the process of creating crops that exhibit higher resistance to pests, diseases, and the effects of climate change. Genomic selection algorithms employed to examine extensive sets of genetic data, detecting characteristics linked to drought tolerance, resistance to pests, or enhancement in crop yield. CRISPR-Cas9 gene editing tools assist in choosing and developing gene editing techniques, forecasting the results of genetic alterations [73].

The development of biodegradable plastics derived from renewable biological sources plays a crucial role in addressing the worldwide plastic pollution issue by providing eco-friendly materials that decompose naturally and minimize harm to the environment. Utilizing artificial intelligence can assist in the development and evaluation of novel bioplastic substances, examining their degradability, durability [74], and various characteristics to pinpoint the most viable options for industrial applications. Material science AI systems that model and forecast the characteristics of bioplastic materials, speeding up the search for novel, sustainable polymers. Lifecycle Analysis (LCA) AI tools that assess the ecological consequences of bioplastics throughout their lifecycle, providing guidance for sustainable manufacturing methods [59].

Biotechnology provides solutions for addressing air pollution through the creation of plants and microbes capable of absorbing or decomposing harmful gases, ultimately enhancing air quality. Artificial intelligence models replicate air movement and pollution distribution, assisting in identifying the most suitable plant species for particular air pollutants in urban development. Air quality prediction models that employ historical and current data to predict pollution levels, which will assist in deciding where to plant biofiltration green spaces [75]. AI-driven environmental monitoring networks of sensors collect data that artificial intelligence (AI) utilizes to detect the origins of pollution and propose methods for reducing its impact.

Biotechnology aids in the conversion of organic waste into valuable resources such as compost or biofuels, thereby diminishing the need for landfills and minimizing greenhouse gas emissions. Artificial intelligence has the capability to continuously monitor and regulate the conditions during composting or anaerobic digestion procedures, ensuring the ideal functioning of microorganisms for accelerated waste decomposition. AI-controlled bioreactors systems employ sensors and AI algorithms to adapt environmental conditions in real-time, enhancing microbial activity and expediting waste decomposition. AI-driven robots (Waste Sorting Robots) with advanced visual capabilities are employed to effectively segregate organic waste from other forms, thereby enhancing the overall efficiency of biodegradation procedures [76].

Innovative biotechnological techniques effectively capture and store carbon dioxide from the atmosphere, thereby aiding in the fight against climate change through the reduction of greenhouse gas emissions. By analyzing environmental and biological data, AI identifies the most effective strategies for biological carbon capture, enhancing the contribution of biotech solutions to climate change mitigation. Research into genetic modifications to improve plant photosynthesis is supported by AI, aiming to increase carbon capture by plants. AI-optimized Carbon Capture and Storage (CCS) systems simulate and optimize the processes of capturing carbon dioxide and storing it underground or in materials [77].

Biotechnology assists in developing eco-friendly agricultural practices, such as using biopesticides and biofertilizers, reducing chemical runoff and soil degradation. AI models predict the runoff risks of different agricultural practices, helping in the design of bio-based solutions that reduce nutrient leaching [78]. AI-driven systems analyze crop health and soil conditions, recommending precise application of bio pesticides and bio fertilizers to minimize runoff. Crop rotation AI models predict the best crop rotation strategies to maintain soil health and reduce chemical inputs, leveraging historical data and machine learning.

Challenges

Pharmaceutical companies may have access to vast data sets containing millions of compounds for drug development, which can pose challenges for traditional machine learning tools [10]. Despite their potential, there are challenges associated with using ANNs in personalized medicine. The accuracy of ANNs relies heavily on the quality and quantity of data they are trained on [79]. Designing and engineering biomolecules raises ethical questions [80]. Careful consideration is needed to ensure the responsible development and use of these technologies. Regulatory bodies are still developing frameworks for AI-driven bio manufacturing processes [6]. Addressing these regulations requires clear documentation and the validation of AI models. Implementing and maintaining AI systems requires a skilled workforce with expertise in both bioprocessing and data science [81]. CRISPR technology raises ethical debates due to its ability to alter human genes and the potential for misuse [82]. Not all research labs may have easy access to advanced AI tools due to their high cost or the required technical expertise.

Future Directions

With the continuous advancement of AI and robotics technologies, we anticipate a further proliferation of groundbreaking applications in biotechnology. This strong combination has the potential to completely transform the industry and result in innovations in bioengineering, medicine development, and healthcare. Preventive medicine is an upcoming phenomenon associated with personalized medicine [83, 84]. AI has the potential to assist in the creation of CRISPR systems for intricate gene editing assignments, such as the insertion or removal of extensive DNA segments [85]. The CRISPR workflow can be automated in a number of ways, including genetic sequence analysis, experiment design, and data interpretation with the help of AI. This speeds up the rate of discovery and frees up researchers' time for more difficult tasks [86]. However, it is crucial to acknowledge the current limitations and potential shortcomings of AI tools in biotechnology. Despite their predictive power through regression analysis, these tools often exhibit a bias towards past findings, which may constrain "out of the box" thinking and limit novel predictions. Additionally, AI algorithms do not inherently assess the credibility of the data they process, meaning that they can produce inaccurate conclusions if fed with false or misleading information. Addressing these prospective issues is essential for the future development of AI in biotechnology. By improving data validation processes and developing more sophisticated algorithms that can account for data quality, we can mitigate these risks and harness the full potential of AI to drive innovation in the field.

Conclusion

Artificial intelligence (AI] stands at the forefront of innovation, transforming various industries and bringing about a revolution in scientific research. Within the field of biotechnology, AI has completely transformed the processes of drug discovery, personalized medicine, and genome editing methods such as CRISPR technology. Moreover, AI-powered solutions are actively tackling environmental issues by promoting renewable energy production, bioremediation, and enhancing the resilience of plants. Although ethical concerns and accessibility issues arise from the integration of AI in biotech, the continuous advancement of AI and biotechnology promises transformative applications that can result in breakthroughs in health and well-being, drug development, and environmental management. This collaboration between AI and biotechnology shows great potential for tackling global challenges and fostering sustainable innovation.

Author's Contribution

All authors contributed to conceptualization, writing, review and editing. All authors read and approved the final manuscript.

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