



A Review on the Impact of Biotechnology on Agriculture, Medicine, Industries and the Environment

Rita M. Sunday*, Chiamaka R. Iwuozor, Inikpi R. Ujah-Samuel, Zainab R. Ibrahim, Nuratu Yussuff, Titi M. Asala and Nma H. Ifedilichukwu

Medical Biotechnology Department, National Biotechnology Research and Development Agency, Abuja, Nigeria.

Corresponding Author: reetersun@gmail.com

Abstract

Biotechnology utilises living organisms to create new products intended to improve human health, agriculture and the environment. Biotechnology has been applied since ancient times to date, and it has made significant strides in recent years in agriculture, medicine, the environment and industries. The objective of this article is to carry out a critical review of the impact of biotechnology in agriculture, medicine, industries, and the environment using standard procedures. The types and innovations of biotechnology are also discussed in this paper. Innovations in biotechnology include targeted therapies, drug development, gene editing, biofuels, bioremediation and immunotherapy. Biotechnology has helped in the production of valuable products such as pest-resistant plants, hybrid livestock, vaccines, insulin, antibiotics, biogas, biofertilizers, and biopesticides.

Keywords: Agriculture, biotechnology, impact, innovations, medicine.

Introduction

Biotechnology can be defined as the use of living organisms or their processes in the creation of products or processes, and it has become an integral part of modern life (Tasnim, 2024). This innovative sector changes the world across various industries, serving as a critical engine for economic growth, environmental sustainability, and industrial innovation globally. Biotechnology has undergone significant evolution from its traditional roots to modern applications (Lu et al., 2024). Biotechnology has been used to produce essential products including antibiotics, bread, cheese, yoghurt and vaccines (Jackson et al., 2020; Gupta et al., 2017). The development of biotechnology is divided into ancient biotechnology, classical biotechnology and modern biotechnology.

Ancient biotechnology (pre-1800s) has to do with early human applications of biological processes, mainly in agriculture, food production, and traditional medicine, without a scientific understanding of microorganisms or genetics (Chaachouay and Zidane, 2024). The process used in ancient biotechnology includes selective breeding and fermentation (Ray et al., 2024; Stenseth et al., 2022). Fermentation dates to early civilisations where yeast and bacteria were used for brewing beer, making wine and fermenting dairy products like yoghurt and cheese (Ray et al., 2024). Selective breeding was used in the domestication of crops and animals for improved traits, such as drought resistance in crops and hybridization in livestock (Ahmadzai et al., 2024; Stenseth et al., 2022). The impact of ancient biotechnology includes cheese and leavened bread making; traditional antibiotics production; beer brewing and wine making; food preservation; flavour enhancement; and traditional medicine (Ray et al., 2024; Gaynes, 2017; Chaachouay and Zidane, 2024).

Classical biotechnology (1800s - mid-20th century) encompasses the period from the 19th century to the mid-20th century, and it is marked by significant scientific discoveries in biochemistry, genetics and microbiology, which laid the groundwork for modern biotechnology. The discoveries during the times of classical biotechnology include fermentation and pasteurization; production of

antibiotics, vaccines and vitamins; principles of genetics; production of enzymes; chemotherapy, production of hybrid corn and development of industrial fermentation (Ray and Joshi, 2014; Gaynes, 2017; Trüeb, 2023; McGovern et al., 2004; Hegreness and Meselson, 2007; Mackin and Walker, 2021; Steele, 2000). Modern biotechnology (1950s - present) marks an era of rapid innovation driven by groundbreaking discoveries in molecular biology, genetic engineering and computational biology. Key developments during this period include molecular biology revolution, recombinant DNA technology and genetic engineering; polymerase chain reaction (PCR); genomics; CRISPR and genome editing; and digital technologies. The molecular biology revolution has to do with the discovery of the DNA double helix structure, which was discovered by Watson and Crick (Raju, 2016; Watson and Crick, 1953). This discovery laid the foundation for understanding genetic information. Advances in molecular biology also enhanced the study of gene structure and function. The advent of recombinant DNA technology and genetic engineering allowed scientists to manipulate and recombine genetic material from different organisms. The development of cloning and gene expression systems spurred innovations in medicine, agriculture, and industrial biotechnology. Polymerase Chain Reaction (PCR), invented by Kary Mullis in the 1980s, revolutionised the field of molecular biology by allowing rapid and exponential amplification of specific DNA segments (Lorenz, 2012). This breakthrough has had profound impacts on diagnostics, forensic science, and research. Genomics and the human genome project, which was completed in 2003, provided a complete map of the human genetic code, and this created new avenues for personalised medicine and genomics research (Taylor et al., 2024; Brlek et al., 2024). Advances in high-throughput sequencing and bioinformatics further accelerated the pace of discovery (Mardis, 2013; Debasis et al., 2022; Zhang et al., 2024). The development of CRISPR-Cas9 technology and genome editing has transformed genetic engineering by enabling precise, efficient and cost-effective genome editing (Aljabali et al., 2024). This technology holds promises for treating genetic diseases, improving crop resilience, and advancing synthetic biology.

Modern biotechnology integrates digital technologies, artificial intelligence, complex data analytics, and automation, thereby enhancing research capabilities and industrial processes (Jumper, 2021). These tools are pivotal in accelerating drug discovery, optimising bioprocesses and developing novel therapeutic strategies. The impact, including types and innovations of biotechnology in agriculture, medicine, industries and the environment, is discussed in this review article.

Materials and Methods

A literature search was conducted across multiple electronic databases, including PubMed, Google Scholar, Research Gate, Semantic Scholar, Science Direct and Medline. Appropriate search terms and combinations were used, including “biotechnology”, “biotechnology impact”, “biotechnology products”, “types of biotechnology”, and “biotechnology innovations”, etc. Inclusion criteria included the availability of the whole paper, only peer-reviewed journal articles and English as the language of communication.

Results and Discussion

Types of Biotechnology

The types of biotechnology include green, red, white, blue, dark, yellow, violet, grey, brown and gold biotechnology (Table 1).

- *Green biotechnology (Agricultural biotechnology)*: This is an important field of modern biotechnology used in agriculture, and it involves processes used for improving agricultural products. Green biotechnology has to do with crop improvement and production of novel plant products, which is achieved by implanting gene(s) of interest into plant species, which in turn, helps in increasing the crop yield (Gao, 2021). Also in green biotechnology, livestock animals with the most desirable characteristics are bred together to obtain offspring with the desired traits.
- *Red Biotechnology (Medical biotechnology)*: This has to do with health care processes and technologies used for the improvement of human health, and it has helped in the development of new drugs, vaccines, antibodies and therapies for the treatment of diseases (Ma *et al.*, 2024). Red biotechnology is applied in stem cell therapy, which may help in treating diseases, such as Parkinson's disease (Stankiewicz *et al.*, 2024). Gene therapy in red biotechnology has helped in the identification of human hereditary diseases by detecting mutations in a single gene (Bennett *et al.*, 2022).
- *Yellow biotechnology (Food biotechnology)*: This has to do with the improvement of nutrition in food products. It is the oldest form of biotechnology that utilizes enzymatic and microbial processes, as well as genetic and compound modification to improve the nutritional contents of food this includes as wine, cheese, beer and bread (Ray *et al.*, 2014).
- *White biotechnology (Industrial biotechnology)*: Industrial biotechnology involves the use of biological systems such as micro-organisms (bacteria, mould and yeast) in the industrial production of chemicals, biofuels and enzymes (Nielsen *et al.*, 2022; Demain, 2009).
- *Blue biotechnology (Marine biotechnology)*: Blue biotechnology makes use of marine-based organisms and resources to create products and

services. Blue biotechnology helps in the production of biofuel from photosynthetic algae and a painkiller known as Ziconotide from cone snail venom (Blasiak *et al.*, 2023).

- *Grey biotechnology (Environmental biotechnology)*: Environmental biotechnology has to do with the use of biological systems and processes for waste management, environmental protection, waste treatment and environmental restoration (Arun *et al.*, 2024; Ipsita and Munishwar, 2023). This type of biotechnology is centred on environmental applications, maintenance of biodiversity and removal of pollutants using a biotechnology approach. The focus of grey biotechnology is environmental applications such as recovery and preservation of ecosystems, and pollutants removal by using microorganisms to remove contaminants. Grey biotechnology helps in bioremediation, pollution control and maintenance of biodiversity (Arun *et al.*, 2024; Ipsita and Munishwar, 2023).
- *Brown biotechnology (Arid zone or Desert biotechnology)*: This is a field of biotechnology that uses microorganisms and other scientific methods to address environmental challenges (Rodriguez-Nunez *et al.*, 2020). The focus of brown biotechnology is the management of arid and desert lands by addressing challenges in desert and arid regions. Brown biotechnology is similar to grey biotechnology. Brown biotechnology has to do with the treatment of desert-like soils to make them more productive; the development of drought-resistant crops in arid, drought-stricken regions; and water resources management.
- *Gold biotechnology (Bioinformatics or computational biology)*: This has to do with the use of computational methods to solve biological problems. Gold biotechnology involves areas related to bioinformatics (software and hardware) used in data analysis of biological processes which include sequencing peptides; improving industrial enzymes; searching for primers and DNA alterations; analyzing errors in DNA transcription; analyzing evolutionary relationships between species; and discovering industrial enzymes (Debasis *et al.*, 2022; Zhang *et al.*, 2025).
- *Violet biotechnology (Legal biotechnology)*: This is an area of biotechnology that focuses on laws, regulations, ethics and philosophical issues that affect biotechnology. It ensures the safe use of biotechnology as well as patent law and intellectual property rights. It also studies biosecurity and how to protect against threats such as bioterrorism and biological warfare (Bentahar *et al.*, 2023).
- *Dark biotechnology*: This has to do with the use of biotechnology for bioterrorism and biological warfare (Riedel, 2004; Wheelis *et al.*, 2000). It involves the use of microorganisms and toxins to cause diseases and death in humans, animals and crops.

Impact of Biotechnology

Biotechnology has gained recognition in recent times due to its application in different sectors, including agriculture, medicine, environment and industries; and it has also

Table 1. Types of Biotechnology.

S/No.	Types of biotechnology	Focus	References
1.	Green (agricultural biotechnology)	Crops and livestock improvement, which includes pest-resistant plants and livestock animals with desirable traits such as increased milk production by cows.	Gao, 2021
2.	Red (medical biotechnology)	Health care processes which involve the use of technologies that improve human health, such as antibiotics, stem cell therapy and vaccines.	Ma <i>et al.</i> , 2024; Bennett <i>et al.</i> , 2022.
3.	Yellow (food biotechnology)	Improvement of nutrition in food products, such as probiotics.	Ray <i>et al.</i> , 2014
4.	White (industrial biotechnology)	The use of micro-organisms (bacteria and yeast) in the industrial production of chemicals, biofuels and enzymes.	Nielsen <i>et al.</i> , 2022; Demain, 2009
5.	Blue (marine biotechnology)	The use of marine-based organisms and resources to create products such as biofuel.	Blasiak <i>et al.</i> , 2023.
6.	Grey (environmental biotechnology)	The use of biological systems and processes for waste management, environmental protection, waste treatment and environmental restoration.	Arun <i>et al.</i> , 2024; Ipsita and Munishwar, 2023.
7.	Brown (arid zone or desert biotechnology)	Treatment of desert-like soils to make them more productive and the development of drought-resistant crops in arid, drought-stricken regions.	Rodriguez-Nunez <i>et al.</i> , 2020.
8.	Gold (bioinformatics or computational biology)	The use of bioinformatics and computational methods in the analysis of data that has to do with biological processes, which include peptide sequencing and DNA transcription.	Debasis <i>et al.</i> , 2022; Zhang <i>et al.</i> , 2025
9.	Violet (legal biotechnology)	This area focuses on laws, regulations, ethics and philosophical issues that have to do with biotechnology.	Bentahar <i>et al.</i> , 2023
10.	Dark (bioterrorism and biological warfare biotechnology)	This involves the use of biotechnology for bioterrorism and biological warfare.	Riedel, 2004; Wheelis <i>et al.</i> , 2002

Agriculture

Biotechnology has a significant impact on agriculture, with a range of applications that have led to improvements in crop yields, nutritional content, disease resistance, and more sustainable farming practices. In ancient times, selective breeding (hybridisation) was carried out by selectively mating organisms with desirable traits to enhance these traits in their offspring. Selective breeding is done by carrying out genetic selection in plants and livestock for improved traits (Winter and Bill 2022; Ashish *et al.*, 2011).

Modern biotechnology has helped in the production of crops such as genetically modified crops that are resistant to pests and diseases. Genetically modified crops have been especially potent in raising yields, decreasing environmental impacts, and sustaining food security. Genetic modification allows crops to be grown with better traits such as drought tolerance, insect resistance, and higher nutritional values (Kumari *et al.*, 2022; Munaweera *et al.*, 2022). Through enhanced genetic traits, crop yields are increased; however, these crops lessen the need for fertilisers and active ingredients in harmful pesticides and herbicides, thereby reducing the impact on the environment due to chemical use. Promoting sustainable agriculture through genetic engineering acts as a foundation in promoting the conservation of biodiversity and natural resources (Kour *et al.*, 2020). Numerous countries reaped huge economic gains through the adoption of genetically modified herbicide-tolerant (GM HT) soybeans. Argentina, for instance, has had total income benefits amounting to US \$18,567.30 million from cost savings and second crop gains; Brazil and the US meanwhile benefited from cost savings with aggregate income benefits of \$7,220.20 million and \$13,297.30 million, respectively, and Canada have further increased economic benefits with a total income benefit of \$ \$662.8 million (Brookes & Barfoot, 2018).

A standout example is the introduction of Bt brinjal in

yield alongside a 39% reduction in pesticide use, translating into almost US \$400 net income per hectare (Ahmed *et al.*, 2019). In the developing countries, 24 of them account for 56% of global biotech hectares in 2019, while 5 industrial countries took the 44% share (ISAAA, 2021; Tasnim, 2024).

Medicine and healthcare

Biotechnology has become an essential tool in medicine, leading to significant healthcare advancements. Modern biotechnology is at the forefront of healthcare innovation, offering advanced solutions that enhance patient outcomes through targeted therapies (gene therapy), personalised medicine, and novel diagnostic tools. As research progresses, new healthcare technologies promise to further improve the ability to diagnose, treat, and prevent diseases. Biotechnology has facilitated the production of recombinant proteins such as monoclonal antibodies, insulin, and vaccines (Mackin and Walker, 2021; Diem *et al.*, 2022; Ma *et al.*, 2024). Insulin, monoclonal antibodies, and vaccines (including mRNA vaccines) have contributed to the treatment and prevention of various diseases like diabetes, haemophilia, and heart disease (Fardoost *et al.*, 2024; Wang and Wang, 2024).

The development of personalised medicine through pharmacogenomics—tailoring treatments according to individual genetic profiles—enhances drug efficacy and reduces adverse effects. Furthermore, biotechnology-driven innovations play a vital role in medicine, supporting the development of new drugs, vaccines, medical devices, and diagnostic tools aimed at improving patient outcomes, preventing illnesses, and enhancing healthcare overall (Vicente *et al.*, 2024). Examples of biotechnological advances in healthcare include personalised medicine, gene therapy, regenerative medicine, targeted drug delivery systems, and advanced diagnostic imaging techniques (Vicente *et al.*, 2024).

These innovations hold potential to revolutionise

healthcare by offering more effective, precise, and customised solutions to medical challenges while minimising side effects (Koppu *et al.*, 2022; Abinaya and Viswanathan, 2021). Biotechnology in pharmacy (Biopharmaceuticals) also presents significant market opportunities from an economic standpoint. The global biopharmaceutical market has expanded from \$139 billion in 2012 to \$346 billion in 2021, at a CAGR of 10.7%, and is projected to reach \$975 billion by 2030, with an expected CAGR of 12.2% (Etiti *et al.*, 2024).

(Vicente *et al.*, 2024). The biofuel and biorefinery industries have also benefited significantly from biotechnology. Life-cycle analyses show that second-generation ethanol derived from lignocellulosic biomass can reduce greenhouse gas emissions by as much as 80% compared to fossil fuel (Liu *et al.*, 2020). Also, food and beverages such as dairy and plant-based alternatives are produced in food industries by using fermentation processes. Biotechnology applications have significant potential for addressing environmental

Table 2. Impact of Biotechnology on agriculture, medicine, environment and industries

S/No.	Sectors	Impact of Biotechnology	References
1.	Agriculture and food.	• Hybrid livestock. • Hybrid crops. • Genetically modified organisms. • Food preservatives. • Bread. • Beverages. • Yoghurt and cheese. • Wine and beer.	Stenseth <i>et al.</i> , 2022; Pretorius, 2000; Bennett <i>et al.</i> , 2022; Androsavich, 2024,
2.	Medicine and healthcare.	• Monoclonal antibodies. • Insulin. • Vaccines. • Medicines such as antibiotics and analgesics. • Growth hormones • Immunotherapy. • MicroRNAs. • Gene editing. • Personalized medicine. • Treatment of genetic disorders. • Targeted therapies. • Regulation of gene expression • Artificial organs for research • Genetic circuits for medical applications. • Stem cell therapy. • Therapeutic proteins	Sravanthi <i>et al.</i> , 2024; Diem <i>et al.</i> , 2022; Gaynes, 2017; Jumper, 2021; Raper and Chirmule, 2019; Pacesa <i>et al.</i> , 2024; Mandrycky, 2016; Zheng <i>et al.</i> , 2024; Bennett <i>et al.</i> , 2022; Nielsen, 2016; Stankiewicz <i>et al.</i> , 2024; Wu <i>et al.</i> , 2024.
3.	Environment and industries.	• Biodegradable plastics. • Biogas. • Biofertilizers • Biopesticides. • Biofuels and bio-based products. • Enzymes. • Bioremediation. • Genetic circuits for industrial applications.	Nielson <i>et al.</i> , 2022; Venkatesh <i>et al.</i> , 2020; Arun <i>et al.</i> , 2024; Schmid <i>et al.</i> , 2001; McGovern <i>et al.</i> , 200; Nielsen, 2016,

Industries and the Environment

Industrial biotechnology has helped in the production of biodegradable plastics, biofuels, biofertilizers and biopesticides. Biotechnology's impact on environmental preservation is notably underscored by the advancement of biofuels (Vicente *et al.*, 2024). These renewable alternatives to fossil fuels, sourced from organic materials like plant biomass or algae, represent a significant stride in sustainable energy solutions. For instance, a previous study conducted in Egypt showed that High-rate algal ponds (HRAPs) used in wastewater treatment not only achieve biomass yields of up to 27 g m⁻²/day but also remove 99% of pathogens, 61% chemical oxygen demand (COD), 66% biological oxygen demand (BOD) and 65% total suspended solid (TSS) (Doma *et al.*, 2018). While a more recent study showed an increase in the reduction of pathogens, COD, BOD, and TSS to 100%, 82%, 89% and 92% respectively (Abd-Elmaksoud *et al.*, 2021). Leveraging genetic and metabolic engineering techniques (Vicente *et al.*, 2024). It is possible to enhance the efficiency and affordability of biofuel production, further bolstering their potential as a green energy source

pollution through bioremediation techniques that utilise microorganisms to clean contaminated environments (Schmid *et al.*, 2001; Venkatesh *et al.*, 2020; Arun *et al.*, 2024).

Biotechnology has been evolving significantly over the past few decades, transitioning from a specialized scientific field into a multidisciplinary powerhouse with the potential to revolutionize industries, healthcare, agriculture and the environment. Biotechnology innovations have transformed industries and improved healthcare, agriculture and the environment. Biotechnology innovations include immunotherapy, drug development, gene editing, biofuels, bioremediation, treatment of genetic disorders, targeted therapies, improved crop resilience, therapeutic proteins, regeneration of damaged tissues/organs, printing of living tissues/organs, creation of complex tissue structures, regulation of gene expression and genetically modified organisms (Table 2).

- **Immunotherapy and Stem Cell Therapy**
Immunotherapy, such as CAR-T cell therapy and

cancer research, is a promising area of biotechnology research that harnesses the body's immune system to fight cancer by manipulating immune cells to target and destroy cancer cells more effectively (Raper and Chirmule, 2019). Immunotherapies offer a more targeted and less invasive alternative to traditional cancer treatments like chemotherapy and radiation. Stem cell therapy holds the potential for regenerating damaged tissues and organs, offering new hope for conditions such as spinal cord injuries and degenerative diseases. Research in this area continues to expand, with applications in personalized therapy (Stankiewicz *et al.*, 2024).

- **MicroRNAs and Artificial Intelligence (AI) technology for drug discovery**

MicroRNAs (miRNAs) are non-coding ribonucleic acid (RNA) molecules that are explored as next-generation diagnostic agents due to their role in regulating gene expression and involvement in the treatment of various diseases (Zheng *et al.*, 2024). Artificial intelligence technology for drug discovery enables researchers to sift through complex data and predict the efficacy of potential drugs faster and more accurately. This transforms the drug discovery processes by reducing the time it takes to produce a new drug while improving the precision of treatments. Artificial intelligence models, like AlphaFold, enhance drug discovery by predicting protein structures with high accuracy (Jumper, 2021).

- **Gene editing, personalized medicine and treatment of genetic disorders**

Gene editing involves the direct manipulation of an organism's DNA to achieve desired traits. This includes the development of genetically modified organisms (GMOs) that can resist pests or tolerate harsh environmental conditions. Personalized medicine using genomic analysis enables tailored treatments based on individual genetic profiles, improving efficacy and reducing side effects. Gene editing using CRISPR technology allows precise modifications to treat genetic disorders and develop targeted therapies (Pacesa *et al.*, 2024). Gene editing technology such as CRISPR-Cas9 has helped in the modification of genes in cells or organisms and in the treatment of genetic disorders, cancer, sickle cell and infectious diseases (Doudna and Charpentier, 2014; Zhang *et al.*, 2024). Gene editing helps in treating genetic diseases, advancing cancer therapies and improving crop resilience (Bennett *et al.*, 2022).

- **Artificial organs for research and genetic circuits**

Researchers are now able to create complex tissue structures that could be used for drug testing, regenerative medicine, transplantation and disease modelling using synthetic biology and 3D bioprinting technology (Mandrycky, 2016). Synthetic biology combines biology, engineering, and computer science to design and construct new biological parts, devices, and systems for research purposes. Synthetic biology technology is also used for the engineering of artificial cells and genetic circuits for medical and industrial applications (Nielsen, 2016). 3D bioprinting is an emerging technology used for printing living tissues and organs that are used for research related to do with creating tissue structures for regenerative medicine and transplantation (Mandrycky, 2016).

- **Bio-based products**

Bio-based products such as biofuels and biogas are

created using bioengineering technology. Bioengineering is revolutionizing industries from pharmaceuticals to food production, and innovations in this field have led to more sustainable manufacturing processes and the creation of bio-based products that are environmentally friendly (Venkatesh *et al.*, 2020).

- **Recombinant proteins and targeted therapies**

Recombinant proteins include monoclonal antibodies, insulin and vaccines (Androsavich, 2024; Diem *et al.*, 2022; Mackin and Walker, 2021; Hutchings *et al.*, 2019). Insulin is used for the management of diabetes, and monoclonal antibodies are used for targeted treatment of cancer diseases, infections and autoimmune disorders (Diem *et al.*, 2022). Monoclonal antibodies are engineered proteins that have become essential in targeting specific diseases, particularly cancers. For instance, Herceptin (trastuzumab) targets HER2-positive breast cancer cells, improving treatment outcomes while minimizing harm to healthy cells. Monoclonal antibodies are also being developed for autoimmune diseases and neurological disorders, showcasing their versatility in modern medicine (Ma *et al.*, 2024). Targeted therapy helps reduce side effects and improve the stability and absorption of drugs within the body (Wu *et al.*, 2024).

Ethical implications of biotechnology in genetic engineering, human health and biodiversity.

Although the biotechnology sector is amongst the most dynamic areas of modern science, providing opportunities for significant improvement in quality of life, extending life expectancy and solving the global challenges of food security and climate change. These biotechnological advancements raise important ethical considerations which constitute several serious ethical and legal concerns about the endpoints of permissible intervention in processes of nature, particularly those related to genetic engineering, human health and biodiversity (Varypaiev *et al.*, 2025).

Although genetically modified organisms have many benefits, they are also considered to pose a threat to the environment and human health (Anyshchenko, 2019). Therefore, ethical concerns such as informed consent, confidentiality, subjects for research, equal access to the benefits of research, morality, benefits for the person employed for research, such as insurance, intellectual property rights and liability are required to be articulated. Additionally, the control of bioterrorism using genetically engineered surface and drugs to erase memory and the immune system. Hence, the bioethics for the safe regulation of potential benefits of biotechnology and bioengineering and the welfare of mankind and nature is of paramount consideration. Apex regulatory agencies such as the US FDA, Environmental Protection Agency, and ICMR have proposed Ethical Guidelines for biomedical science (Munshi & Sharma, 2018). These regulations and policies differ from country to country. And can be influenced by international agreements and organisations (Dessie and Zegeye, 2024).

Unexpected ethical dilemmas arise in the conservation of selected specific species. And therefore, environmental protection must be seen as a moral obligation for humans (Rozensky *et al.*, 2024), climate change and biodiversity (Williams *et al.*, 2023). Biodiversity collapse is exponentially driving the emergence and spread of infectious diseases with extreme weather events, direct and indirect consequences, which, without immediate action, human health will be compromised (Engwa, 2014).

However, biotechnology advancements in human

genetics leading to the development of new diagnostic tools, therapies, and personalised treatment strategies raise important ethical considerations, including concerns about genetic privacy, germline editing, and access to healthcare. The application of genetic engineering brings with it ethical issues and therefore must be seriously guided by laws and standard ethical systems. It is essential to address these challenges to ensure that the benefits of these technologies are used responsibly and equitably. So that man will not be a victim of his discoveries to advance the moral and scientific well-being of mankind (Babale Y. K. & Atoi E. N., 2021).

Biotechnology and genetic engineering also raise significant ethical concerns across human health and biodiversity. These include potential for genetic discrimination, unequal access to advancements, and the alteration of natural ecosystems. Adequate understanding and control of the subject matter are imperative to minimise the risk of irreversible harm to the environment and human health. Careful consideration of these implications is crucial to ensure responsible development and application of these technologies.

Conclusion

This review highlighted that biotechnology has a significant impact on agriculture, medicine, industries, and the environment by providing innovative and sustainable solutions to these sectors. The contribution of biotechnology to these sectors has been invaluable. Biotechnology has helped in enhancing food security in agriculture; development of new drugs, vaccines, and diagnostic tests in medicine; addressing energy challenges by developing renewable sources of energy, such as biofuels and biogas in industries; and development of bioremediation processes in the environment. Looking ahead, the future direction of biotechnology is promising, with potential advancements in personalised medicine, genetic engineering, and sustainable agricultural practices on the horizon. The integration of biotechnology with fields like artificial intelligence and nanotechnology could lead to unprecedented solutions that further enhance efficiency and sustainability across diverse applications.

However, this growth is not without challenges. Ethical concerns surrounding genetic modifications, regulatory hurdles, and public perception may impede progress. Additionally, ensuring equitable access to biotechnological innovations will be crucial to prevent widening disparities in health and food security. As we continue to harness its potential, it is essential to foster an environment that encourages responsible research and practices, inviting collaboration among scientists, policymakers, and the public. By doing so, we can ensure that biotechnology not only meets today's needs but also paves the way for a more sustainable and equitable future for all.

Recommendations

Agriculture: There should be training and support for sustainable biotechnology farming practices to reduce environmental impact. The public should be educated about genetically modified organisms (GMOs) to counter misinformation. Also, regulations should be done responsibly to ensure biosafety and biodiversity protection.

Medicine: There should be more investment in research and development for gene editing, regenerative medicine, and vaccine innovation. Equitable access to biotechnological healthcare, especially in low-income regions, should be promoted, and regulations for safety, ethics, and privacy in genetic data use should be strengthened.

Environment: Research on microbial and enzymatic solutions for pollution should be expanded, and green technologies like bioenergy and biodegradable materials should be incentivized. Also, the ecological impact of released genetically engineered organisms should be monitored.

Industries: Biotechnology innovation in clean manufacturing and synthetic biology should be encouraged. There should be foster public-private partnerships for tech transfer and scale-up. Standards and certifications for bio-based products should be developed.

Declaration of interest

The authors declare no conflict of interest.

References

1. Abd-Elmaksoud, S., Abdo, S.M., Gad, M., Hu, A., El-Liethy, M.A., Rizk, N., Marouf, M.A., Hamza, I.A., and Doma, H.S. (2021). Pathogens removal in a sustainable and economic high-rate algal pond wastewater treatment system. *Sustainability*, 13(23): 13232. <https://doi.org/10.3390/su132313232>
2. Abinaya, R. V., and Viswanathan, P. (2021). Biotechnology-based therapeutics. In *Translational Biotechnology* (pp. 27-52). Academic Press. <https://doi.org/10.1016/B978-0-12-821972-0.00019-8>
3. Adetoyinbo, A., Gupta, S., Okoruwa, V. O., and Birner, R. (2022). The role of institutions in sustaining competitive bioeconomy growth in Africa-Insights from the Nigerian maize biomass value-web. *Sustainable Production and Consumption*, 30:186-203. <https://doi.org/10.1016/j.spc.2021.11.013>
4. Ahmadzai, A. S, Hu, C., Amin, A. K. and Zahed, Z. (2024). Exploring the journey of plant breeding from ancient traditional practices to modern advancements. *Journal of Crop Improvement*, 38(6), 688-709. <https://doi.org/10.1080/15427528.2024.2391423>.
5. Ahmed, A., Hoddinott, J. F., Abedin, N., and Hossain, N. Z. (2019). Economic and health impact of genetically modified eggplant: Result from a randomised controlled trial of Bt-brinjal in Bangladesh (IFPRI Discussion Paper No. 1866). International Food Policy Research Institute (IFPRI).
6. Aljabali, A. A., El-Tanani, M. and Tambuwala, M. M. (2024). Principles of CRISPR-Cas9 technology: advancements in genome editing and emerging trends in drug delivery. *Journal of Drug Delivery Science and Technology*, 105338. <https://doi.org/10.1016/j.jddst.2024.105338>
7. Androsavich, J. R. (2024). Frameworks for transformational breakthroughs in RNA-based medicines. *Nature reviews: Drug discovery*, 23(6), 421-444. <https://doi.org/10.1038/s41573-024-00943-2>.
8. Anyshchenko A., 2019. The Precautionary Principle in EU Regulation of GMOs: Socio-Economic Considerations and Ethical Implications of Biotechnology. *Journal of Agricultural and Environmental Ethics* 32(5), Pg. 855-872
9. Arun, K. A., Martolia, S., Dohroo, A., Al-Tawaha, A. R. M. S. and Malik, T. (2024). Exploring bioremediation strategies for heavy metals and POPs pollution: the role of microbes, plants, and nanotechnology. *Frontiers in Environmental Science*, 12, 1397850. <https://doi.org/10.3389/fenvs.2024.1397850>
10. Ashish, S. V., Shishir, A., Shruti, R. and Anchal, S. (2011). Biotechnology in the Realm of History. *Journal of Pharmacy and Bioallied Sciences*, 3(3), 321-323. <https://doi.org/10.4103/10975-7406.844430>

11. Babale Y. K. and Atoi E. N., 2021. Ethical Concerns and Risk Perceptions Associated with the Application of Genetic Engineering. *Journal of Social Sciences* 7(3). Pg. 231-238.
12. Backhouse, M., and Lorenzen, K. (2021). Knowledge production and land relations in the bioeconomy. A case study on the Brazilian sugar-bioenergy sector. *Sustainability*, 13(8), 4525. <https://doi.org/10.3390/su13084525>
13. Bennett, J., Wellman, J. A. and Marshall, K. A. (2022). Gene Therapy for Inherited Retinal Diseases. *Annual Review of Medicine*, 73, 147-162. <https://doi.org/10.1146/annurev-med-042420-092822>
14. Bentahar, S., Abada, R. and Ykhlef, N. (2023). Biotechnology: Definitions, types and main applications. *YMER*, 22(4), 563 - 575. <https://doi.org/10.37896/ymer22.04/49>
15. Bentahar, S., Abada, R., and Ykhlef, N. (2023). Biotechnology: Definitions, types and main applications. *Ymer*, 22(4), 563-575.
16. Blasiak, R., Jouffray, J. B., Amon, D. J. and Claudry, J. (2023). Making marine biotechnology work for people and nature. *Journal of Nature and Evolution*, 7 (4), 482-485.
17. Bringezu S, Distelkamp M, Lutz C, Wimmer F, Schalbach R, Hennenberg KJ, Böttcher H, Egenolf V (2021) Environmental and socioeconomic footprints of the German bioeconomy. *Nature Sustainability*, 4:775-783. <https://doi.org/10.1038/s41893-021-00725-3>
18. Brlek, P., Bulić, L., Bračić, M., Projić, P., Škaro, V., Shah, N., Shah, P. and Primorac, D. (2024). Implementing Whole Genome Sequencing (WGS) in Clinical Practice: Advantages, Challenges, and Future Perspectives. *Cells*, 13(6), 504. <https://doi.org/10.3390/cells13060504>
19. Brookes, G., and Barfoot, P. (2018). Environmental impacts of genetically modified (GM) crop use 1996-2016: Impacts on pesticide use and carbon emissions. *GM Crops and Food*, 9(3), 109-139. <https://doi.org/10.1080/21645698.2018.1476792>
20. Brookes, G., and Barfoot, P. (2022). GM crops: Global socio-economic and environmental impacts 1996-2020. *GM Crops and Food*, 13(1), 1-32. <https://doi.org/10.1080/21645698.2022.2108391>
21. Calicioglu, Ö., and Bogdanski, A. (2021). Linking the bioeconomy to the 2030 sustainable development agenda: Can SDG indicators be used to monitor progress towards a sustainable bioeconomy? *New Biotechnology*, 61:40-49. <https://doi.org/10.1016/j.nbt.2020.10.010>
22. Chaachouay, N. and Zidane, L. (2024). Plant-derived natural products: a source for drug discovery and development. *Drugs and Drug Candidates*, 3(1), 184-207. <https://www.mdpi.com/2813-2998/3/1/11#>.
23. Craig, V., and Daniel, C. (2004). The Century of Biology. *New Perspect.* 21:73-77.
24. Das, S., Ray, M.K., Panday, D., Mishra, P.K. (2023). Role of biotechnology in creating sustainable agriculture. *PLOS Sustain Transform* 2(7):e0000069. Doi: 10.1371/journal.pstr.0000069
25. Debasis, M., Debanjan, M., Mohamed, S. B., Somya, S., Kumud, P., Manu, P., Ankita, P., Pallavi, S., Saliha, D., Leila, H., Periyasamy, P., Pradeep, K. D. M. (2022). Evolution of bioinformatics and its impact on modern bio-science in the twenty-first century: Special attention to pharmacology, plant science and drug discovery. *Computational Toxicology*, 24, 100248. <https://doi.org/10.1016/j.comtox.2022.100248>.
26. Demain, A. L. (2009). Biotechnology and the Study of Natural Products. *Journal of Industrial Microbiology and Biotechnology*, 36(9), 1059-1064. <https://doi.org/10.1007/s10295-009-0616-1>
27. Dessie A. M and Zegeye Z. B., 2024. Review on Public perception of biotechnology on genetically modified crops, bio policy and intellectual property rights. *American Journal of Polymer Science and Technology* 10 (2), 26 - 35.
28. Diem, P., Ducluzeau, P. H., and Scheen, A. (2022). The discovery of insulin. *Diabetes Epidemiology and Management*, 5, 100049. <https://doi.org/10.1016/j.deman.2021.100049>
29. Doma, H. S., Abdo, S. M., Hemdan, B. A., and Ali, G. H. (2018). Research article enhancing biomass, energy, and value-added compounds yield from pilot pilot-scale pond system. *Journal of Environmental Science and Technology*, 11:199-208. DOI: 10.3923/jest.2018.199.208
30. Doudna, J. A. and Charpentier, E. (2014). The new frontier of genome engineering with CRISPR-Cas9. *Science*, 346(6213), 1258096. <https://doi.org/10.1126/science.1258096>.
31. Engwa G. A., 2014. Genetic engineering on microorganisms: the ecological and bioethical implications. *European Journal of Biotechnology*, 1(3): 27-33.
32. Ethical challenges in Biotechnology: Exploring the boundaries of scientific intervention. 17(1):1-20.
33. Etit, D., Meramo, S., Ögmundarson, Ö., Jensen, M. K., and Sukumara, S. (2024). Can biotechnology lead the way toward a sustainable pharmaceutical industry? *Current Opinion in Biotechnology*, 87:103100. <https://doi.org/10.1016/j.copbio.2024.103100>
34. Fardoost, A., Karimi, K., Govindaraju, H., Jamali, P. and Javanmard, M. (2024). Applications of microfluidics in mRNA vaccine development: A review. *Biomicrofluidics*, 18(6), 061502. <https://doi.org/10.1063/5.0228447>.
35. Fetting, C. (2020). The European Green Deal. ESDN report, December 2(9):53. https://www.esdn.eu/fileadmin/ESDN_Reports/ESD_N_Report_2_2020.pdf
36. Gao, C. (2021). Genome engineering for crop improvement and future agriculture. *Cell*, 184(6), 1384-1400. <https://doi.org/10.1016/j.cell.2021.01.015>.
37. Gaynes, R. (2017). The discovery of penicillin—new insights after more than 75 years of clinical use. *Emerging Infectious Diseases*, 23(5), 849. <https://doi.org/10.3201/eid2305.161556>.
38. Gupta, V., Sengupta, M., Prakash, J. and Timothy B. C. (2017). An introduction to biotechnology. *Journal of Basic and Applied Aspects of Biotechnology*, 1-21.
39. Hegreness, M. and Meselson, M. (2007). What did Sutton see? Thirty years of confusion over the chromosomal basis of Mendelism. *Genetics*, 176(4), 1939-1944. <https://doi.org/10.1534/genetics.104.79723>.
40. Hutchings, M. I., Truman, A. W. and Wilkinson, B. (2019). Antibiotics: past, present and future. *Current opinion in microbiology*, 51, 72-80.
41. Ipsita, R. and Munishwar, N. G. (2023). White and grey biotechnologies for shaping a sustainable future. *Royal Society of Chemistry Sustainability*, 1: 1722-1736. <https://doi.org/10.1039/d3su00174a>.
42. ISAAA. (2021). Global status of commercialised biotech/GM crops: 2021. ISAAA Brief No. 57. ISAAA: Ithaca, NY. <https://www.isaaa.org/resources/publications/briefs/default.asp>
43. Jackson, N. A., Kester, K. E., Casimiro, D., Gurunathan, S. and DeRosa, F. (2020). The promise of mRNA vaccines: a review. *Expert Review of Vaccines*, 19(2), 151-164. <https://doi.org/10.1080/14760584.2020.1714715>.
44. Jumper, J. (2021). Highly accurate protein structure prediction with AlphaFold. *Nature*, 596(7873), 583 -

589. <https://doi.org/10.1038/s41586-021-03819-2>.
45. Koppu, V., Poloju, D., Puvvala, B., Madineni, K., Balaji, S., Sheela, C.M.P., Manchikanti, S.S.C. and Moon, S.M. (2022). Current perspectives and future prospects of mRNA vaccines against viral diseases: a brief review. *International Journal of Molecular and Cellular Medicine*, 11(3): 260. doi: 10.22088/IJMCM.BUMS.11.3.260
46. Kour, D., Rana, K.L., Yadav, A.N., Yadav, N., Kumar, M., Kumar, V., Vyas, P., Dhaliwal, H.S., and Saxena, A.K. (2020). Microbial biofertilizers: Bioresources and eco-friendly technologies for agricultural and environmental sustainability. *Biocatalysis and Agricultural Biotechnology*, 23:101487. <https://doi.org/10.1016/j.bcab.2019.101487>
47. Kumari, P., Jasrotia, P., Kumar, D., Kashyap, P.L., Kumar, S., Mishra, C.N., Kumar, S., and Singh, G.P. (2022). Biotechnological approaches for host plant resistance to insect pests. *Frontiers in Genetics*, 13: 914029. <https://doi.org/10.3389/fgene.2022.914029>
48. Liu, F., Short, M.D., Alvarez-Gaitan, J.P., Guo, X., Duan, J., Saint, C., Chen, G., and Hou, L.A. (2020). Environmental life cycle assessment of lignocellulosic ethanol-blended fuels: A case study. *Journal of Cleaner Production*, 245:118933. <https://doi.org/10.1016/j.jclepro.2019.118933>
49. Lorenz, T. C. (2012). Polymerase chain reaction: basic protocol plus troubleshooting and optimization strategies. *J Vis Exp.*, 22(63), e3998. <https://doi.org/10.3791/3998>
50. Lu, Q., Tang, D., Liang, Q. and Wang, S. (2024). Biotechnology for the degradation and upcycling of traditional plastics. *Environmental Research*, 15,263(part 2), 120140. <https://doi.org/10.1016/j.envres.2024.120140>
51. Lu, Z., Yuan, Y., Han, Q., Wang, Y., and Liang, Q. (2024). Lab-on-a-chip: an advanced technology for the modernisation of traditional Chinese medicine. *Chinese Medicine*, 19(1), 80.
52. Ma, Q., Durga, P., Wang, F. X. C., Yao, H. P. and Wang, M. H. (2024). Pharmaceutical innovation and advanced biotechnology in the biotech-pharmaceutical industry for antibody-drug conjugate development. *Drug Discovery Today*, 29(8), 104057. <https://doi.org/10.1016/j.drudis.2024.104057>
53. Mackin, D. W., and Walker, S. P. (2021). The historical aspects of vaccination in pregnancy. *Best Practice and Research Clinical Obstetrics and Gynaecology*, 76, 13-22. <https://doi.org/10.1016/j.bpobgyn.2020.09.005>.
54. Mandrycky, C., Wang, Z., Kim, K., and Kim, D. H. (2016). 3D bioprinting for engineering complex tissues. *Biotechnology Advances*, 34(4), 422-434. <https://doi.org/10.1016/j.biotechadv.2015.12.011>.
55. Mardis, E. R. (2013). Next-generation sequencing. *Journal of Clinical Oncology*, 31(15), 1925-1930. <https://doi.org/10.1200/JCO.2012.45.0714>.
56. McGovern, P. E., Zhang, J., Tang, J., Zhang, Z., Hall, G. R., Moreau, R. A., Nunez, A., Butrym, E. D., Richards, M. P., Wang, C., Cheng, G., Zhao, Z. and Wang, C. (2004). Fermented beverages of pre-and proto-historic China. *Proceedings of the National Academy of Sciences*, 101(51), 17593-17598. <https://doi.org/10.1073/pnas.040792110>.
57. Munaweera, T. I. K., Jayawardana, N. U., Rajaratnam, R., and Dissanayake, N. (2022). Modern plant biotechnology as a strategy in addressing climate change and attaining food security. *Agriculture and Food Security*, 11(1): 1-28. <https://doi.org/10.1186/s40066-022-00369-2>
58. Munshi A. and Sharma V., 2018. Safety and ethics in biotechnology and bioengineering: what to follow and what not to. *Journal of Omics Technologies and Bio-Engineering*. Pg 577-590.
59. Nielsen, A. A., (2016). Genetic circuit design automation. *Science*, 352(6281), aac7341. <https://doi.org/10.1126/science.aac7341>
60. Nielsen, J., Tillegreen, C. B., and Petranovic, D. (2022). Innovation trends in industrial biotechnology. *Trends in Biotechnology*, 40(10), 1160-1172. <https://doi.org/10.1016/j.tibtech.2022.03.007>
61. Pacesa, M., Pelea, O., and Jinek, M. (2024). Past, present, and future of CRISPR genome editing technologies. *Cell*, 187(5), 1076-1100. <https://doi.org/10.1016/j.cell.2024.01.042>
62. Pretorius, I. S. (2000). Tailoring wine yeast for the new millennium: novel approaches to the ancient art of winemaking. *Yeast*, 16(8), 675-729. [https://doi.org/10.1002/1097-0061\(20000615\)16:8<675::AID-YEA585>3.0.CO;2-B](https://doi.org/10.1002/1097-0061(20000615)16:8<675::AID-YEA585>3.0.CO;2-B)
63. Raju, P. (2016). World history of modern biotechnology and its applications. *Biotechnology: an Indian Journal*, 12(11), 107.
64. Raper, S. E. and Chirmule, N. (2019). Gene therapy: Promises and problems. *Medical Clinics*, 103(2), 337-353. <https://doi.org/10.1016/j.mcna.2018.10.003>
65. Ray, R. C. and Joshi, V. K. (2014). Fermented foods: past, present and future. *Microorganisms and Fermentation of Traditional Foods*, 1-36.
66. Ray, R. C., Paramithiotis, S., Thekkangil, A., Nethravathy, V., Rai, A. K. and Martin, J. G. P. (2024). Food Fermentation and Its Relevance in Human History. In *Trending Topics on Fermented Foods* (pp. 1-57). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-72000-0_1
67. Riedel, S. (2004). Biological warfare and bioterrorism: a historical review. *Baylor University Medical Center Proceedings*, 17(4): 400-406. <https://doi.org/10.1080/08998280.2004.11928002>.
68. Rippe K.P., Willemsen A., 2018. *Frontiers in Plant Science* 9(1868).
69. Rodriguez-Nunez, K., Rodriguez-Ramos, F. and Ibanez, C. (2020). Brown biotechnology: a powerful toolbox for resolving current and future challenges in the development of arid lands. *Journal of Applied Sciences and Environmental Science*, 2(1187).
70. Ronzon, T., Piotrowski, S., Tamosiunas, S., Dammer, L., Carus, M., and M'barek, R. (2020). Developments of economic growth and employment in bioeconomy sectors across the EU. *Sustainability*, 12(11): 4507. <https://doi.org/10.3390/su12114507>
71. Rozensky L., Vrba Z., Lipa J., Dolista J., 2024. Ethical Challenges in relation to nature and biodiversity. *Ukrainian Journal of Ecology* 14(5), 1-8.
72. Schmid, A., Dordick, J. S., Hauer, B., Kiener, A., Wubbolts, M. and Witholt, B. (2001). Industrial biocatalysis today and tomorrow. *Nature*, 409(6817), 258-268. <https://doi.org/10.1038/35051736>.
73. Sravanthi, K., Sattiraju, K. S., Paul, S., Nihal, N. G., Salunkhe, S., and Mane, S. V. (2024). Robert Koch: From Anthrax to Tuberculosis-A Journey in Medical Science. *Cureus*, 16(11), e72955. <https://doi.org/10.7759/cureus.72955>.
74. Stankiewicz, L. N., Rossi, F. M. V. and Zandstra, P. W. (2024). Rebuilding and rebooting immunity with stem cells. *Cell Stem Cell*, 31(5), 597-616. <https://doi.org/10.1016/j.stem.2024.03.012>.
75. Steele, J. H. (2000). History, trends, and extent of pasteurization. *Journal of the American Veterinary Medical Association*, 217(2), 175-178. <https://doi.org/10.2460/javma.2000.217.175>.
76. Stenseth, N. C., Andersson, L. and Hoekstra, H. E. (2022). Gregor Johann Mendel and the development of modern evolutionary biology. *Proceedings of the*

- National Academy of Sciences*, 119(30), e2201327119.
<https://doi.org/10.1073/pnas.2201327119>.
77. Tasnim, N. (2024). Understanding the impacts of biotechnology: a survey among the university students in Chittagong (Doctoral dissertation, Brac University).
https://dspace.bracu.ac.bd/xmlui/bitstream/handle/10361/23987/18136071_MNS.pdf?sequence=1&disAllowed=y
 78. Taylor, D. J., Eizenga, J. M., Li, Q., Das, A., Jenike, K. M., Kenny, E. E., Miga, K. H., Monlong, J., McCoy, R. C., Paten, B. and Schatz, M. C. (2024). Beyond the Human Genome Project: The Age of Complete Human Genome Sequences and Pangenome References. *Annual Review of Genomics and Human Genetics*, 25(1), 77-104.
<https://doi.org/10.1146/annurev-genom-021623-081639>.
 79. Trüeb, R. M. (2023). Brief History of Microbiology. In *Hair in Infectious Disease: Recognition, Treatment, and Prevention* (pp. 1-17). Cham: Springer International Publishing.
https://doi.org/10.1007/978-3-031-30754-6_1.
 80. Varypaiev, O., Serohina, H., Serediuk, N., Dorozhko, I., and Silvestrova, O. (2025). Ethical challenges in biotechnology: exploring the boundaries of scientific intervention. *Synesis*. Universidade Católica de Petrópolis, Rio de Janeiro, Brasil 17 (1):1-20.
 81. Venkatesh, A., Posen, I. D., MacLean, H. L., Chu, P. L., Griffin, W. M. and Saville, B. A. (2020). Environmental Aspects of Biotechnology. *Advances in Biochemical Engineering Biotechnology*, 2020,173:77-119.
https://doi.org/10.1007/10_2019_98
 82. Vicente, H., Neves, J., and Figueiredo, M. (2024). Evaluating the Perceptions of the Portuguese Population on the Economic Impacts of Biotechnology-Based Technologies. *Sustainability*, 16(8): 3307. <https://doi.org/10.3390/su16083307>
 83. Wang, N. and Wang, T. (2024). Innovative translational platforms for rapid developing of clinical vaccines against COVID-19 and other infectious disease. *Biotechnology Journal*, 19(2), 2300658.
<https://doi.org/10.1002/biot.202300658>.
 84. Watson, J. D. and Crick, F. H. C. (1953). A Structure for Deoxyribose Nucleic Acid. *Nature*, 171(4356), 737-738. <https://doi.org/10.1038/171737a0>.
 85. Wei, X., Luo, J., Pu, A., Liu, Q., Zhang, L., Wu, S., Long, Y., Leng, Y., Dong, Z. and Wan, X. (2022). From biotechnology to bioeconomy: A review of development dynamics and pathways. *Sustainability*, 14(16), 10413. <https://doi.org/10.3390/su141610413>
 86. Wheelis, M. (2002). Biological warfare at the 1346 siege of Caffa. *Emerging Infectious Diseases*, 8(9), 971-975. <https://doi.org/10.3201/eid0809.010536>.
 87. Williams P. C., Beardsley J., Isaacs D., Preisz A., Marais B. J., 2023. The impact of climate change and biodiversity loss on the health of children: An ethical perspective. *Frontiers in public health* 10, 1048317.
 88. Winter, S. and Bill, T. (2022). The future of genetic engineering in Biotechnology. *Journal of Applied Biotechnology and Bioengineering*, 9(1), 1-3.
<https://doi.org/10.15466/jab.2022.09.00276>.
 89. Wu, Y., Sun, B., Tang, Y., Shen, A., Lin, Y., Zhao, X., Li, J., Monteiro, M. J. and Gu, W. (2024). Bone targeted nano-drug and nano-delivery. *Bone Research*, 12(1), 51.
<https://doi.org/10.1038/s41413-024-00356-2>.
 90. Yasmen, S. (2023). Future research and challenges of industrial biotechnology. *International Research Journal of Biotechnology*, 14(2): 1-4
<https://www.interestjournals.org/articles/future-research-and-challenges-of-industrial-biotechnology.pdf>
 91. Zhang, M. L., Li, H. B., and Jin, Y. (2024). Application and perspective of CRISPR/Cas9 genome editing technology in human diseases modeling and gene therapy. *Frontiers in Genetics*, 15, 1364742.
 92. Zhang, S., Liu, K., Liu, Y., Hu, X. and Gu, X. (2025). The role and application of bioinformatics techniques and tools in drug discovery. *Frontiers in Pharmacology*, 16, 1547131.
<https://doi.org/10.3389/fphar.2025.1547131>.
 93. Zheng, J., Yang, B., Liu, S., Xu, Z., Ding, Z. and Mo, M. (2024). Applications of Exosomal miRNAs from Mesenchymal Stem Cells as Skin Boosters. *Biomolecules*, 14(4), 459.
<https://doi.org/10.3390/biom14040459>.