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Recent Advances in Human Health Through Biotechnology

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ABSTRACT

Biotechnology has emerged as one of the most transformative fields in modern science, fundamentally reshaping the landscape of human health. By integrating principles from molecular biology, genetics, bioinformatics and engineering, biotechnology offers innovative solutions to some of the most pressing healthcare challenges, including infectious diseases, chronic illnesses and genetic disorders. This manuscript provides a comprehensive exploration of the role of biotechnology in advancing human health, focusing on key areas such as genetic engineering, vaccine development, regenerative medicine, diagnostics and personalized medicine. The discussion also highlights recent technological breakthroughs, ethical considerations and future prospects. Through these advancements, biotechnology continues to improve life expectancy, enhance quality of life and provide sustainable approaches to global health challenges.

Keywords: Biotechnology, Human Health, Genetic Engineering, Vaccines, Diagnostics, Personalized Medicine, Regenerative Medicine

1. Introduction

Biotechnology is a multidisciplinary science that uses biological systems and processes to address scientific, technological and healthcare challenges[1-3]. Its roots date back to ancient times, when humans selected plants for cultivation, domesticated animals and used microorganisms to produce bread, wine and beer. At that time, there was no scientific knowledge available nor the means to acquire this knowledge about the underlying processes and molecules and people relied on experience for breeding of plant and animal species and fermentation[4,5]. Throughout history, scientists have tried to explain these phenomena. However, it was only during the second half of the19thcentury, when biotechnology gained a rigorous scientific basis: Louis Pasteur identified and isolated yeast as the agent responsible for the transformation of must into wine, Gregor Mendel formulated the laws of genetics and Friedrich Miescher discovered nucleic acids[5,6]. Biotechnology refers to the application of biological systems, living organisms or their derivatives to develop products and technologies that improve human life. Over the past few decades, biotechnology has revolutionized healthcare by enabling the development of innovative therapies, diagnostic tools and preventive strategies (Pandit, 2022). From the production of insulin using recombinant DNA technology to the rapid development of vaccines against emerging infectious diseases, biotechnology has become indispensable in modern medicine.

The advancement of human health through biotechnology is driven by continuous scientific discoveries and technological innovations[1,3]. These developments have significantly enhanced our understanding of disease mechanisms at the molecular level, paving the way for targeted interventions. This review explores the major contributions of biotechnology to human health and examines its potential to address future healthcare challenges.

1.1. Historical evolution of biotechnology in healthcare

The roots of biotechnology can be traced back to ancient civilizations that utilized fermentation processes for food and beverage production[3-5]. However, modern biotechnology began to take shape in the 20th century with the discovery of DNA structure and the development of genetic engineering techniques. the History of Medicine and Biotechnology cover several topics including: the pioneering medieval medical schools, recombinant DNA, the development of recombinant insulin and its impact on diabetes management, the groundbreaking advances in AIDS therapy and diagnosis, the history of cell cultures and stem-cell research, the development of monoclonal antibodies, the Human Genome Project, Assisted Reproduction and gene therapy[1,6].

1.2. Development of recombinant DNA technology

However, the discovery of the structure of DNA by James Watson and Francis rick and the development of DNA synthesis by Arthur Kornberg in the 1950s marked a watershed moment and led to the birth of genetic engineering and recombinant DNA (rDNA) technology. These enabled David Goeddel's group at Genentech, the first biotech company[1,5,6], in 1978, to produce recombinant human insulin in Escherichia coli. It was the first in vitro animal-free, non-immunogenic recombinant protein and quickly became the standard therapy for treating diabetes patients worldwide[7,8]. Genentech's success inspired many new paradigms for disease diagnosis and treatment as well as the start of many other biotechnology companies. The 1990s witnessed the Human Genome Project and the first gene therapies in humans, notably Alain Fischer's successful cure of a rare and severe immune deficiency[8,9]. In 1995, the first genome of a living organism, Haemophilus influenzae, was sequenced and 2 years later, the cloning of the sheep Dolly demonstrated the potential of cellular manipulation in mammals. The growing knowledge about recombinant DNA technology further paved the way for genome editing, which achieved its first tangible results in 2005 by using zinc finger nucleases (ZFNs) and the transcription activator-like effector nucleases (TALENs) in 2010. Nevertheless, CRISPR-Cas gene-editing technology, based on a natural bacterial defense mechanism, was developed in 2013[3-5]. It allows the precise manipulation of DNA by adding, deleting or replacing specific genes or individual nucleotides in living cells[9-11]. During the same period, mRNA attracted interest as a therapeutic tool. In late 1987, Robert Malone took the first steps toward RNA therapeutics by mixing mRNA with lipidic droplets that were able to enter living human cells. However, until the late 2000s, the development of mRNA therapies was held back by RNA's instability and high production costs. Nonetheless, the idea of mRNA vaccines gained traction in oncology, albeit as a therapeutic agent rather than to prevent disease[1,8]. Several scientists and start-up companies explored the technology to combat cancer through the expression of mRNA-encoded proteins to stimulate the immune system against tumor cells. In 2008, both Novartis and Shire established mRNA research units, the former focused on vaccines, the latter on therapeutics. Moderna was one of the companies that built on this work and, by 2015, it had raised more thanUS$1 billion on the promise of harnessing mRNA to restore missing or defective disease-causing proteins. When that plan faltered, Moderna chose to prioritize vaccines. When COVID-19 struck, Moderna quickly created a prototype vaccine within days after the virus's genome sequence became available and started human trials within less than ten weeks[1,8,11]. BioNTech partnered with Pfizer in March 2020 and clinical trials moved at a record pace, going from first-in-human testing to emergency approval in less than 8months. Both vaccines use modified mRNA formulated in lipid nanoparticles (LNPs), containing sequences that encode a form of the SARS-CoV-2 spike protein to induce protective immunity. The mRNA vaccines greatly contributed to fight the pan demic spread of SARS-CoV-2 virus infection[8,12].

These milestones laid the foundation for the biotechnology revolution in healthcare. The ability to manipulate genetic material opened new possibilities for treating diseases at their root cause.

2. Modern Era Developments

Modern biotechnology emerged in the early 20th century. A turning point came in 1928 with the discovery of penicillin by Alexander Fleming who accidentally observed that a mold, later identified as a rare strain of Penicillium Notatum, inhibited the growth of Staphylococcus colonies on a Petri dish[4,12]. Fleming obtained an extract from the mold, naming its active agent penicillin and determined that it has an antibacterial effect on staphylococci and other gram-positive bacteria. However, several attempts made by Fleming's group to purify penicillin failed; he eventually published his findings in the British Journal of Experimental Pathology in June 1929 and referred in an elusive manner to penicillin's potential therapeutic benefits). The onset of World War II forced scientists and engineers to collaborate in developing large-scale culture of Penicillium to quickly produce penicillin, facing the need to cure wounded soldiers and civilians[12,13]. This effort has led to the improvement of fermentation technology and made penicillin widely available.

2.1. Genetic engineering and gene therapy

Genetic engineering involves the direct manipulation of an organism's DNA to alter its characteristics[2,4]. This technology has led to the development of gene therapy, which aims to treat or prevent diseases by correcting defective genes.

2.1.1. Principles of genetic engineering: Genetic engineering utilizes tools such as restriction enzymes, vectors and gene-editing systems to modify DNA sequences. CRISPR-Cas9 has emerged as a powerful tool for precise gene editing, allowing scientists to target specific genes with high accuracy[14,15]. This is technology is demonstrated in **(Figure 1)**.

2.1.2. Applications in human health: Genetic engineering has applications in the treatment of genetic disorders such as cystic fibrosis and sickle cell anemia, development of genetically engineered immune cells for cancer therapy and production of therapeutic proteins.

2.1.3. Challenges and ethical considerations in gene therapy: Despite its potential, gene therapy faces challenges such as off-target effects, immune responses and ethical concerns related to genetic modification. Addressing these issues is critical for the safe and effective application of genetic engineering in healthcare[2-5].

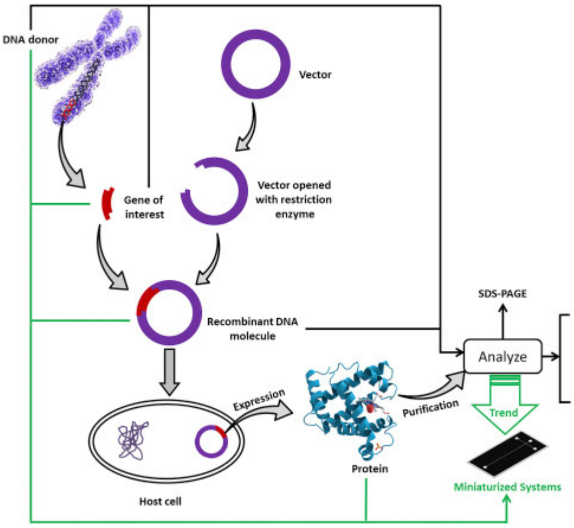


Figure 1: Advancing Human Health Through Recombinant DNA Technology.

2.2. Vaccine development and immunotherapy

2.2.1. Vaccines: Vaccines are one of the most successful applications of biotechnology in preventing infectious diseases. Biotechnology has enabled the development of advanced vaccines that are safer, more effective and faster to produce[8,15-17].

Vaccines are biological preparations that stimulate the immune system to recognize and fight specific pathogens such as viruses or bacteria. Traditional vaccines include live-attenuated and inactivated forms, while newer approaches use subunit, vector-based and nucleic acid technologies. For example, the success of mRNA vaccines during the COVID-19 pandemic demonstrated how quickly vaccines can be designed once the genetic sequence of a pathogen is known[8, 18-20].

The development process typically involves:

- Antigen identification (selecting the target molecule).
- Preclinical testing (in vitro and animal studies).
- Clinical trials (Phase I–III to assess safety and efficacy).
- Regulatory approval and mass production.

Advances in Genomics and Proteomics have significantly accelerated vaccine discovery by identifying potential antigens more efficiently[8,12].

2.2.2. Immunotherapy: Immunotherapy involves enhancing or modifying the immune system to treat diseases, especially cancer, autoimmune disorders and infectious diseases. Unlike vaccines, which are primarily preventive, immunotherapy is often therapeutic[12].

Key types include:

- Monoclonal antibodies targeting specific disease markers.
- Checkpoint inhibitors that release immune "brakes" to attack cancer cells.
- Cell-based therapies, such as CAR-T cell therapy.
- Cytokine therapies to boost immune signaling.

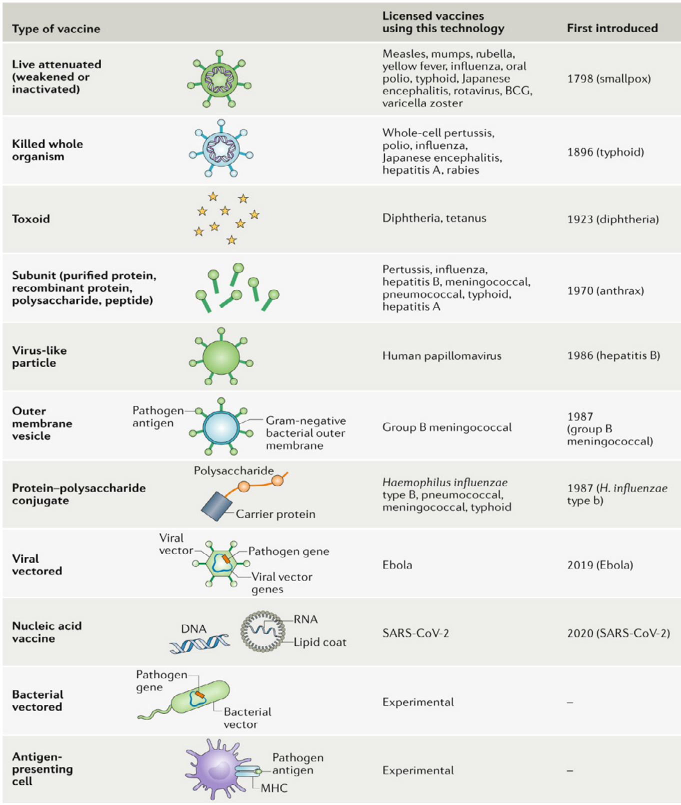
In oncology, immunotherapy has transformed treatment outcomes for diseases like Melanoma and Lung Cancer, offering longer survival rates compared to traditional chemotherapy in some cases[20,21].

Both vaccine development and immunotherapy rely on understanding immune mechanisms. While vaccines aim to prevent disease by building immunity in advance, immunotherapy focuses on treating existing conditions by strengthening or redirecting immune responses. Together, they represent powerful tools in advancing global health[20-22].

2.2.3. Types of biotechnological vaccines: There are six different types of vaccines which are:

- Live attenuated vaccines
- Inactivated vaccines
- Subunit vaccines
- Toxoid vaccines
- Viral vector vaccines
- Messenger RNA vaccines.

However, the above types are comprehensively presented in **(Figure 1)**.



Type of vaccine	Licensed vaccines using this technology	First introduced
Live attenuated (weakened or inactivated)	Measles, mumps, rubella, yellow fever, influenza, oral polio, typhoid, Japanese encephalitis, rotavirus, BCG, varicella zoster	1798 (smallpox)
Killed whole organism	Whole-cell pertussis, polio, influenza, Japanese encephalitis, hepatitis A, rabies	1896 (typhoid)
Toxoid	Diphtheria, tetanus	1923 (diphtheria)
Subunit (purified protein, recombinant protein, polysaccharide, peptide)	Pertussis, influenza, hepatitis B, meningococcal, pneumococcal, typhoid, hepatitis A	1970 (anthrax)
Virus-like particle	Human papillomavirus	1986 (hepatitis B)
Outer membrane vesicle	Group B meningococcal	1987 (group B meningococcal)
Protein–polysaccharide conjugate	*Haemophilus influenzae* type B, pneumococcal, meningococcal, typhoid	1987 (*H. influenzae* type b)
Viral vectored	Ebola	2019 (Ebola)
Nucleic acid vaccine	SARS-CoV-2	2020 (SARS-CoV-2)
Bacterial vectored	Experimental	–
Antigen-presenting cell	Experimental	–

Figure 1: Types of Biotechnology-Based Vaccines.

2.2.4. Role of vaccines in disease prevention: Biotechnological vaccines have played a crucial role in controlling diseases such as hepatitis, influenza and COVID-19. The rapid development of mRNA vaccines demonstrates the power of biotechnology in responding to global health emergencies[12,22-25].

2.3. Diagnostic biotechnology

Accurate and early diagnosis is essential for effective disease management. Biotechnology has revolutionized diagnostics by providing highly sensitive and specific tools[26-28].

2.3.1. Specimens used in diagnostics: Specimens play a central role in advancing human health through biotechnology. They provide the biological material needed for research, diagnostics, drug development and therapeutic innovation[27,28]. Below is a structured overview of the main types of specimens used and how they contribute to modern biotechnology.

2.3.1.1 Human biological specimens: Human biological specimens are samples obtained from the human body for use in medical research, diagnosis and biotechnology. They are essential for understanding disease mechanisms, developing treatments and advancing healthcare[23-25].

Common types of specimens include blood, urine, saliva, tissues and body fluids such as cerebrospinal fluid. Blood samples are widely used to measure biomarkers, detect infections like malaria and HIV/AIDS and assess organ function[8,12,27]. Tissue samples, often collected through biopsy, are important in diagnosing cancers such as prostate cancer and studying cellular changes.

These specimens are used in laboratory analyses including molecular diagnostics, biochemical assays and genetic testing. They help identify pathogens, detect genetic disorders and monitor treatment responses. In research, human specimens support drug development, vaccine production and personalized medicine.

Proper collection, handling, storage and transportation of specimens are critical to maintain their integrity and ensure accurate results. Ethical considerations, including informed consent and confidentiality, are also essential when working with human samples **(Figure 2)**.

Concisely, human biological specimens are fundamental tools in modern healthcare and biotechnology, providing vital information for disease diagnosis, research and treatment advancement[28].

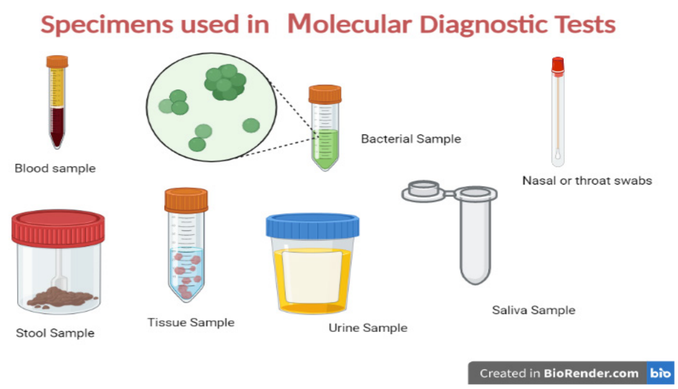


Figure 2: Specimens Used in Molecular Diagnostic Tests.

2.3.1.2. Microbial specimens: Microbial specimens are samples that contain microorganisms such as bacteria, viruses, fungi and parasites. They are widely used in healthcare, research and biotechnology to study disease-causing agents and beneficial microbes[2,3].

These specimens can be obtained from clinical sources (e.g., blood, sputum, urine or swabs) or from the environment (soil, water, air). In medical laboratories, microbial specimens are essential for diagnosing infectious diseases such as tuberculosis, malaria and COVID-19[8,11]. Techniques like culture, microscopy and molecular diagnostics are used to identify and characterize microorganisms[29,30].

In biotechnology, microbial specimens play a crucial role in producing antibiotics, enzymes, vaccines and other bio-products. For example, bacteria like Escherichia coli are commonly used in genetic engineering and recombinant DNA technology to produce proteins such as insulin[29].

Proper collection, preservation and handling of microbial specimens are important to prevent contamination and ensure accurate results. Sterile techniques and appropriate storage conditions must be maintained.

However, microbial specimens are vital for disease diagnosis, scientific research and industrial applications, making them indispensable in advancing healthcare and biotechnology.Top of Form

2.3.1.3 Plant specimens: Plant specimens are samples obtained from plants, such as leaves, stems, roots, seeds or flowers, used in research, medicine and biotechnology. They are valuable sources of bioactive compounds, enzymes and genetic material that contribute to advancing healthcare and agriculture[4].

In medicine, plant specimens are widely used for drug discovery and development. Many therapeutic compounds are derived from plants; for example, Catharanthus roseus produces alkaloids used in cancer treatment[4]. Plants also provide important enzymes like amylases and oxidases[32] used in biochemical and industrial processes.

In biotechnology, plant specimens are used in genetic engineering to improve crop yield, resistance to pests and nutritional quality[4]. Techniques such as tissue culture allow the rapid propagation of disease-free plants, while molecular studies help identify useful genes for crop improvement.

Plant specimens also play a role in environmental sustainability, including the study of plant-based solutions for pollution control and soil improvement.

Proper collection and preservation are essential to maintain the quality and integrity of plant specimens. This includes careful handling, appropriate storage conditions and accurate labeling.

In summary, plant specimens are essential resources in biotechnology, contributing to drug development, agricultural advancement and environmental management.Top of Form

2.3.1.4. Animal specimens: Animal specimens are biological samples obtained from animals for use in research, medical studies and biotechnology. These specimens may include whole organisms, tissues organs, blood or cells and they are essential for understanding biological systems and disease processes[4,12].

In biomedical research, animal specimens are commonly used as models to study human diseases such as diabetes mellitus and cancer. They help scientists investigate disease mechanisms, test new drugs and evaluate the safety and effectiveness of treatments before clinical trials in humans. Animals like mice, rats and rabbits are frequently used due to their genetic and physiological similarities to humans[12].

Animal specimens also contribute to vaccine development, toxicological testing and the study of organ function. In biotechnology, genetically engineered animals are used to produce therapeutic proteins and to study gene expression and regulation.

Ethical considerations are very important in the use of animal specimens. Researchers must follow strict guidelines to ensure humane treatment, minimize suffering and use alternatives whenever possible.

Animal specimens are crucial in advancing scientific knowledge and improving healthcare, serving as vital tools in research, drug development and biotechnology.Top of Form

Specimens from human tissues to microbes and environmental samples are the foundation of biotechnology. They enable breakthroughs in disease diagnosis, drug development, vaccine production and personalized medicine[14]. As biotechnology advances, the ethical collection, storage and use of these specimens (biobanking) become increasingly important to ensure responsible and impactful scientific progress[1].

2.4. Molecular diagnostics

Molecular diagnostics is a branch of biotechnology that analyzes biological markers at the DNA, RNA or protein level to detect and monitor diseases, guide treatment decisions and support personalized medicine[17]. Unlike conventional diagnostic methods, it focuses on the genetic and molecular basis of disease, offering higher sensitivity and specificity. Techniques such as PCR, DNA sequencing and microarrays enable the detection of genetic mutations and pathogens at an early stage[2,3].

2.4.1. Principle of molecular diagnostics

Molecular diagnostics is a field of laboratory medicine that detects diseases by analyzing genetic material such as DNA and RNA, as well as specific proteins. It provides highly sensitive and specific results, enabling early and accurate diagnosis of various conditions[12,14].

This approach relies on identifying unique molecular signatures associated with diseases. Techniques such as polymerase chain reaction (PCR), DNA sequencing and gene expression analysis are commonly used. These methods can detect very small amounts of genetic material, making them especially useful for identifying infections and genetic disorders[28].

Molecular diagnostics is widely applied in detecting infectious diseases like COVID-19 and tuberculosis. It is also essential in diagnosing inherited conditions such as sickle cell anemia and in identifying mutations involved in cancers like breast cancer[17,28].

In addition, molecular diagnostics supports personalized medicine by helping clinicians choose treatments based on an individual's genetic profile. It is also used to monitor disease progression and response to therapy.

Despite its advantages, challenges include high cost, need for specialized equipment and technical expertise. However, ongoing advancements are making these technologies more accessible.

Molecular diagnostics is a powerful tool in modern healthcare, improving disease detection, treatment decisions and patient outcomes.

2.4.2. Biomarkers: Biomarkers are biological indicators used to detect diseases and monitor treatment responses. Biotechnology has facilitated the discovery of novel biomarkers for various diseases[34,35].

2.4.2.1. Biomarkers in healthcare: Biomarkers are measurable biological indicators that play a crucial role in improving health care delivery. They provide objective information about normal physiological processes, disease conditions and responses to treatment, enabling more accurate and timely medical decisions.

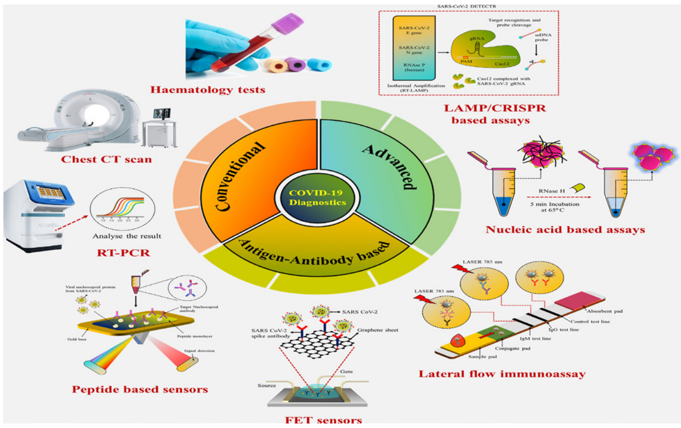


Figure 3: Molecular Diagnostic Techniques in Health Care[33].

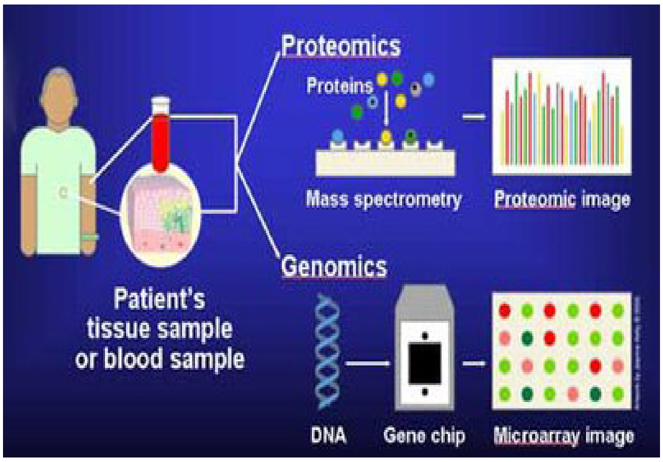


Figure 4: Molecular Diagnostic Techniques in Health Care (Genomics for analyzing DNA, while Proteomics for Proteins)[33].

In clinical practice, biomarkers are widely used for early disease detection, diagnosis and monitoring. For example, blood glucose levels are essential in managing diabetes, while biomarkers such as viral load are used to monitor infections like HIV/AIDS[8,12]. In oncology, specific biomarkers help identify and guide treatment for cancers such as breast cancer, allowing for targeted therapies[28].

Biomarkers also support personalized medicine by helping clinicians select the most effective treatments based on individual patient characteristics. This improves treatment outcomes, reduces adverse drug reactions and enhances overall efficiency in healthcare delivery[2-4].

Despite their benefits, challenges such as high costs, limited accessibility and variability among patients remain. However, continuous advancements in biotechnology are making biomarker-based approaches more reliable and widely available. Biomarkers significantly enhance healthcare delivery by enabling early diagnosis, guiding treatment decisions and improving patient outcomes[35].Top of Form

Molecular diagnostics is a cornerstone of modern biotechnology, bridging laboratory science and clinical medicine. By focusing on the molecular basis of disease, it allows earlier, more accurate diagnoses and supports the shift toward personalized healthcare[35-37].

2.5. Regenerative medicine and tissue engineering

Regenerative medicine aims to repair or replace damaged tissues and organs using biological approaches. This field combines stem cell biology, biomaterials and engineering techniques. Regenerative medicine and tissue engineering are rapidly advancing fields aimed at restoring or replacing damaged tissues and organs[38-40]. They combine principles from biology, medicine and engineering to repair the body's structure and function, offering new hope for conditions that were once considered untreatable. Regenerative medicine focuses on stimulating the body's natural healing processes using approaches such as stem cell therapy, gene therapy and biologically active molecules[38]. Stem cells, particularly pluripotent cells, have the ability to differentiate into various cell types, making them valuable for repairing tissues like skin, bone and nerve cells.

Tissue engineering, a key component of regenerative medicine, involves creating artificial tissues in the laboratory. This is achieved by combining three essential elements: scaffolds, cells and growth factors. Scaffolds provide a structural framework, cells populate the scaffold and growth factors promote cell growth and differentiation. These engineered tissues can then be implanted into patients to restore function[40].

Applications of these technologies include treatment of burns using engineered skin, repair of damaged cartilage and development of artificial organs such as bladders and blood vessels. They are also being explored for treating chronic diseases like heart disease and diabetes[14].

Despite their promise, challenges remain, including high costs, ethical concerns (especially with stem cell use) and difficulties in replicating complex organ structures. However, ongoing research continues to improve their safety and effectiveness[41-43].

More importantly, regenerative medicine and tissue engineering represent a transformative approach in healthcare, with the potential to revolutionize treatment by moving beyond symptom management to actual tissue and organ restoration **(Figure 5)**.

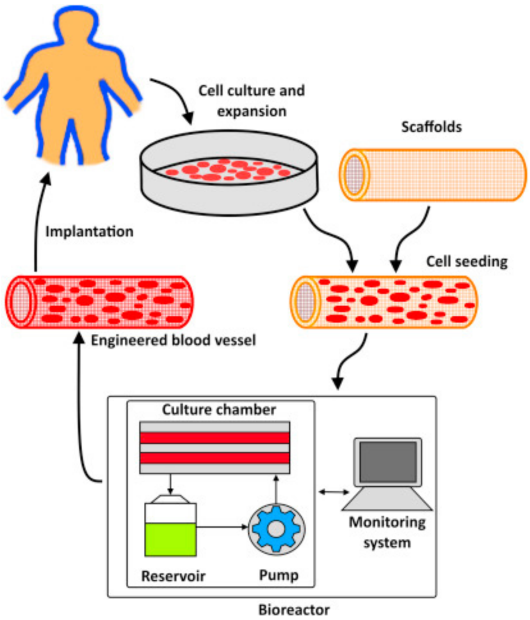


Figure 5: Tissue Engineering Workflow[44].

Tissue engineering flow refers to the step-by-step process used to create functional biological tissues in the laboratory for medical use[38-40]. It typically involves the following key stages:

- **Cell isolation and selection:** Suitable cells are obtained from a patient or donor. These may include stem cells or specialized cells capable of growth and regeneration.
- **Cell expansion (Culturing):** The isolated cells are grown under controlled laboratory conditions to increase their number while maintaining their viability and function.
- **Scaffold preparation:** A biocompatible scaffold is designed to act as a structural framework. It mimics the natural extracellular matrix and supports cell attachment and growth.
- **Cell seeding:** The cultured cells are carefully placed onto or within the scaffold to ensure uniform distribution.
- **Growth and differentiation:** The cell-scaffold construct is maintained in a controlled environment, often using a bioreactor. Growth factors and nutrients are supplied to promote tissue formation and specialization.
- **Tissue maturation:** The developing tissue is allowed to mature and gain functional properties similar to natural tissue.
- **Implantation:** The engineered tissue is implanted into the patient to repair or replace damaged tissue[31].

However, as demonstrated in **(Figure 5)**, tissue engineering flow integrates cells, scaffolds and biological signals in a controlled sequence to produce functional tissues for therapeutic applications.

2.6. Stem cell therapy

Stem cells have the ability to differentiate into various cell types, making them valuable for treating conditions such as spinal cord injuries and degenerative diseases[46, 47].

Stem cell engineering is a branch of biotechnology that involves manipulating stem cells to develop, repair or replace damaged tissues and organs. Stem cells are unique because they can self-renew and differentiate into specialized cell types such as muscle, nerve or blood cells[45,47].

There are different types of stem cells used in engineering. Embryonic stem cells have high differentiation potential, while adult stem cells (e.g., from bone marrow) are more limited but widely used in therapy. Induced pluripotent stem cells (iPSCs) are adult cells that have been reprogrammed to behave like embryonic stem cells, offering a powerful and ethically favorable alternative[48,49].

The process of stem cell engineering typically involves isolating stem cells, culturing and expanding them in the laboratory and directing their differentiation using growth factors, signaling molecules or genetic modification. Advanced tools like CRISPR-Cas9 can be used to edit genes within stem cells to correct genetic defects or enhance therapeutic potential[2,4].

Applications of stem cell engineering are wide-ranging. It is used in regenerative medicine to repair tissues such as skin, bone and cardiac muscle. It also plays a role in treating diseases like leukemia through bone marrow transplantation and in modeling diseases for drug testing and research[31,49].

Despite its promise, stem cell engineering faces challenges including ethical concerns, risk of immune rejection and potential for uncontrolled cell growth. However, ongoing research continues to improve its safety and effectiveness.

More importantly, stem cell engineering is a transformative field with the potential to revolutionize healthcare by enabling tissue regeneration, disease modeling and personalized treatment approaches[16].

2.7. Stem cells and cell cultures

Stem cells are used in regenerative medicine and cell cultures allow controlled experimentation in vitro. Applications include tissue engineering and organ regeneration. Examples include: Induced pluripotent stem cells (iPSCs) for disease modeling[49].

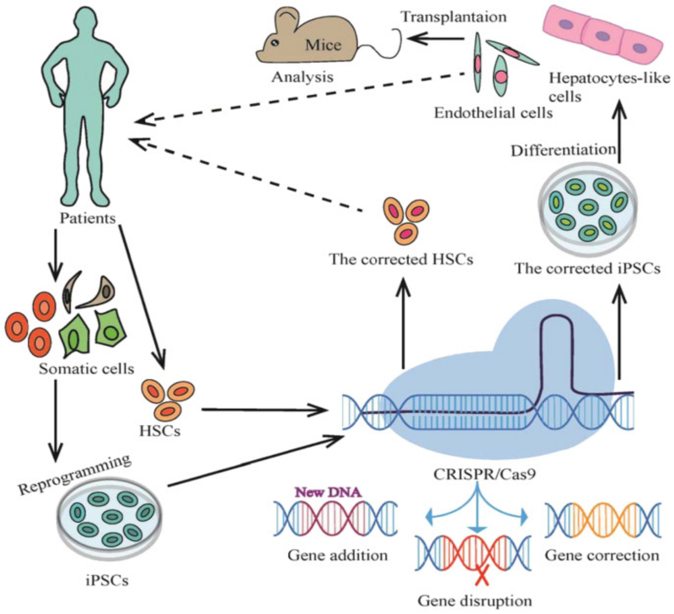


Figure 6: Stem Cell in Advancing Human Health (Sabitha et al., 2021).

2.7. Personalized medicine

Personalized medicine, also known as precision medicine, is an approach to healthcare that tailor's medical treatment to the individual characteristics of each patient. It uses information about a person's genetic makeup, environment and lifestyle to guide decisions related to prevention, diagnosis and therapy[9,16].

At the core of personalized medicine is the analysis of genetic variations. Techniques from molecular biology help identify mutations or biomarkers associated with specific diseases. For example, genetic testing can detect conditions like sickle cell anemia or determine susceptibility to diseases such as breast cancer. This allows healthcare providers to choose treatments that are more effective and less likely to cause adverse effects[48,49].

A key component of personalized medicine is pharmacogenomics, which studies how genes influence a person's response to drugs. This helps in selecting the right medication and dosage for each patient, reducing trial-and-error prescribing. Advanced technologies like CRISPR-Cas9 and next-generation sequencing have further enhanced the ability to customize treatments[2,4].

Applications of personalized medicine include targeted cancer therapies, tailored drug prescriptions and early disease detection[49-52]. It is also used in managing chronic and infectious diseases such as HIV/AIDS, where treatment can be adjusted based on individual response[8].

Despite its advantages, challenges remain, including high costs, data privacy concerns and limited access in some regions. However, as technology advances, personalized medicine is becoming more accessible and is transforming healthcare from a one-size-fits-all approach to more precise, patient-centered care[49].

Nevertheless, personalized medicine improves treatment outcomes by aligning medical care with each individual's unique biological profile, making healthcare more effective and efficient.

2.8. Genomics and precision medicine

Advances in genomics have made it possible to identify genetic variations that influence disease risk and treatment response[2,3]. The rapid evolution of biomedical and digital health sciences, including genomics, proteomics, pharmacogenomics, bioinformatics, real-world data analytics, molecular diagnostics and advanced therapies such as cell and gene therapies and recognizing the cross-cutting and enabling role of artificial intelligence in supporting these domains, which collectively underpin precision medicine and have the potential to transform prevention, diagnosis and treatment across the life course[1,4,49]. However, precision medicine refers to the use of clinical, molecular, genomic and other health-related data to inform prevention, diagnosis and treatment decisions, taking into account individual variability in clinical characteristics, molecular and genomic profiles, with appropriate safeguards, including the use of health technology assessment, to promote ethical, equitable and cost-effective implementation and improved health outcomes[9,16]. Moreover, precision medicine represents a paradigm shift towards predictive, preventive and participatory health systems, enabling targeted, effective and efficient interventions that enhance the efficiency and sustainability of universal health coverage by ensuring that the right intervention reaches the right patient. Furthermore, precision medicine, through genomic sequencing, high-throughput diagnostics and molecular targeting and through the development and delivery of advanced therapies such as cell and gene therapies has shown measurable clinical benefit and in several cases demonstrated cost-effectiveness, including by improving survival through targeted cancer therapies, shortening the diagnostic odyssey for rare diseases, reducing adverse drug reactions through pharmacogenomics[16,17]. The contribution of precision medicine to the prevention and management of noncommunicable diseases, infectious diseases, maternal, child and mental healthcare and its potential to improve health outcomes and greater health system efficiency. The global investment in precision medicine is projected to grow substantially by 2030, reflecting its growing impact on clinical innovation, biotechnology and public health and the need to foster such investment yields equitable and sustainable benefits across all regions. Recalling, as appropriate, the 2023 United Nations high-level meeting on universal health coverage and the 2030 Agenda for Sustainable Development including commitments to promote equitable distribution of and increased access to quality, safe, effective, affordable and essential medicines, vaccines, diagnostics and health technologies, as enablers of affordable, quality healthcare services and their timely delivery for all throughout the life course[1,2,50]. In addition, the role of precision medicine in advancing universal health coverage and the WHO Fourteenth General Program of Work (GPW 14), 2025-2028, particularly in strengthening primary healthcare, ensuring equity and addressing health inequalities. More importantly, many populations, particularly women, children and older adults, remain underrepresented in the data and research that underpin precision medicine and emphasizing the need to ensure diversity and inclusivity in the research and application of precision medicine, including meaningful representation of developing countries and historically underrepresented regions, so that emerging approaches equitably benefit all populations[10,18,20].

2.9. Pharmacogenomics

Pharmacogenomics is the study of how an individual's genetic makeup influences their response to drugs. It combines pharmacology and genomics to develop personalized treatment strategies that maximize drug effectiveness while minimizing adverse effects[51-54].

Genetic variations can affect how drugs are absorbed, metabolized and eliminated in the body. For example, differences in liver enzymes can cause some individuals to process medications too quickly or too slowly, leading to reduced efficacy or increased risk of toxicity[20,27]. Pharmacogenomic testing helps identify these variations before treatment begins.

This approach is widely used in managing diseases such as cancer, where specific genetic markers guide the use of targeted therapies and HIV/AIDS, where drug selection can be optimized for better outcomes[8]. It also plays a role in treating cardiovascular and psychiatric conditions by helping clinicians choose the most suitable medications and dosages.

The benefits of pharmacogenomics include improved drug safety, reduced trial-and-error prescribing and enhanced treatment outcomes[20]. However, challenges such as high costs, limited access to testing and ethical concerns regarding genetic data remain.

Therefore, pharmacogenomics is a key component of personalized medicine, enabling healthcare providers to tailor drug therapy based on an individual's genetic profile, thereby improving the quality and effectiveness of care[2].

2.10. Biotechnology in combating infectious diseases

Biotechnology plays a vital role in preventing, diagnosing and treating diseases by applying biological systems and modern technologies[1,4,52]. It has transformed healthcare by enabling more precise, effective and rapid responses to both infectious and non-communicable diseases[18,20].

One major contribution of biotechnology is in disease diagnosis. Techniques such as molecular diagnostics allow early detection of infections like COVID-19 and tuberculosis, improving treatment outcomes. These methods are highly sensitive and can identify diseases even before symptoms appear[53-55].

Biotechnology is also essential in drug and vaccine development. Through genetic engineering, scientists can produce vaccines and therapeutic proteins efficiently. For example, insulin used in managing diabetes is produced using recombinant DNA technology[14,20]. Vaccines developed using biotechnology have been crucial in controlling infectious diseases worldwide.

Biotechnology plays a critical role in the prevention, diagnosis and treatment of infectious diseases by applying advanced biological and molecular techniques. It has significantly improved the ability to respond to outbreaks and manage diseases effectively. One major contribution is in rapid and accurate diagnosis. Molecular diagnostic tools, such as PCR and nucleic acid sequencing, enable early detection of pathogens responsible for diseases like COVID-19, malaria and tuberculosis[8,54]. Early detection helps in timely treatment and reduces disease spread.

Biotechnology is also central to vaccine development. Modern techniques, including recombinant DNA technology and mRNA platforms, have accelerated the production of safe and effective vaccines. These vaccines stimulate the immune system to recognize and fight infectious agents[54].

In treatment, biotechnology enables the production of antibiotics, antiviral drugs and monoclonal antibodies. Genetic engineering allows microorganisms to produce therapeutic substances efficiently, improving drug availability and effectiveness[20,38].

Additionally, biotechnology supports disease surveillance and epidemiology by tracking pathogen evolution and transmission patterns. This helps in controlling outbreaks and developing targeted interventions[1,20].

Despite its advantages, challenges such as high costs, antimicrobial resistance and unequal access to technology remain. However, continuous innovation is improving global capacity to combat infectious diseases. More importantly, biotechnology is a powerful tool in fighting infectious diseases, enhancing diagnosis, prevention and treatment and contributing significantly to global health security[16,20].

2.11. Ethical, legal and social implications

Biotechnology has transformed healthcare, but it also raises important ethical, legal and social concerns that must be carefully addressed[1,4,54].

Ethical implications focus on moral questions about the use of biological technologies. Issues include genetic modification, stem cell research and gene editing using tools like CRISPR-Cas9[4-6]. Concerns arise about altering human genes, potential misuse and respect for human dignity. Informed consent and the privacy of genetic information are also critical ethical considerations.

Legal implications involve regulations that govern the use of biotechnology. Governments establish laws to ensure safety, quality and ethical compliance in research and clinical applications. Legal issues include patenting of biological materials, ownership of genetic data and liability in case of harm caused by biotechnological products or procedures[1,55-57].

Social implications relate to how biotechnology affects society as a whole. There are concerns about unequal access to advanced treatments, which may widen the gap between rich and poor. Genetic testing may also lead to discrimination in employment or insurance. Cultural and religious beliefs can influence public acceptance of technologies such as cloning and genetic engineering[20].

Balancing innovation with responsibility is essential. Strong ethical guidelines, clear legal frameworks and public awareness are needed to ensure biotechnology benefits society while minimizing risks. However, the ethical, legal and social implications of biotechnology highlight the need for careful regulation and responsible use to protect individuals and promote equitable access to its benefits.

Over the years, concerns about biotechnology have been inflamed by suspicions that science is merely a tool for a technological imperative[57-59], that because something can be done, it should be done. As modern biology and its applications expanded, so did the demands to control how this knowledge will be used. Starting with the Human Genome Project, ethicists, scientists and lawyers began to work together to assess not only what we can do, but also what we should do. Indeed, the application of specific innovations, such as cloning, whole-genome sequencing or gene editing raises significant ethical, legal and societal issues about the safety and potential impact of genetically modified organisms and possible misuse[59]. Concerns also exist about the long-term environmental consequences of modifying organisms' genomes. Another important challenge is the clinical translation of biotechnology and the difficulties in processing these into commercial products. Indeed, only a few biotech advances have so far resulted in new healthcare tools and treatments[60,61]. The bench-to-bedside translation involves several stages beyond discovery and clinical development: the search for funding, the difficulties in clinical trial design and execution, regulatory approvals, market acceptance and competition with other healthcare industries[13,19,22]. These economic and regulatory factors in addition to the above mentioned ethical, legal and societal issues play important roles in regard to how rapidly and efficiently biotechnology can improve healthcare, the pace with which industry developed and advanced the mRNA vaccines against SARS-CoV2 is an important lesson[19,24,42].

3. Public Perception of Biotechnology

Public perception of biotechnology refers to how people understand, evaluate and respond to biotechnological innovations. It plays a crucial role in determining the acceptance, regulation and successful application of these technologies in society[20,62].

Many people view biotechnology positively because of its benefits in healthcare, agriculture and environmental management. Advances such as vaccines, improved diagnostic tools and treatments for diseases like COVID-19 and cancer have increased public trust and appreciation[8,20,61].

However, concerns also exist. Ethical issues surrounding genetic engineering, cloning and gene editing, especially using tools like CRISPR-Cas9, raise fears about safety, misuse and unintended consequences[61,62]. In agriculture, genetically modified organisms (GMOs) are sometimes viewed with skepticism due to potential environmental and health risks[62].

Public perception is influenced by factors such as education, cultural beliefs, media coverage and trust in scientific institutions. Misinformation or lack of awareness can lead to fear or resistance, while proper education and transparency can improve acceptance[62].

To address concerns, scientists and policymakers must engage the public through clear communication, ethical practices and inclusive decision-making. Building trust is essential for the responsible development and adoption of biotechnology[1,20,62].

More importantly, the public perception of biotechnology is mixed, shaped by both its benefits and concerns and plays a key role in its future development and societal impact.

4. Future Prospects of Biotechnology in Human Health

Biotechnology is poised to revolutionize human health by enabling more precise, effective and personalized approaches to disease prevention and treatment[1,4,62]. Rapid advances in molecular biology, genetics and bioengineering are shaping the future of medicine.

One major prospect is the growth of personalized medicine, where treatments are tailored to an individual's genetic profile. Technologies like CRISPR-Cas9 may allow correction of genetic defects, offering potential cures for inherited conditions such as sickle cell anemia[1,20,63].

Regenerative medicine is another promising area. Stem cell therapies and tissue engineering could enable the repair or replacement of damaged tissues and organs, reducing dependence on organ transplants[31]. This may transform the treatment of conditions like heart disease and spinal injuries.

Biotechnology is also expected to enhance disease diagnosis through faster and more sensitive molecular diagnostic tools, allowing early detection of diseases such as cancer and HIV/AIDS[8,20,64]. Early diagnosis improves treatment outcomes and survival rates. In addition, advances in vaccine development, including mRNA technologies, will strengthen the global response to infectious diseases and future pandemics[6,38,65].

Despite these opportunities, challenges such as ethical concerns, high costs and unequal access remain. Addressing these issues will be essential to ensure that the benefits of biotechnology are widely shared.

The future of biotechnology in human health is highly promising, with the potential to transform healthcare into a more precise, preventive and patient-centered system[66-70].

5. Conclusion

Biotechnology has revolutionized human health by providing innovative solutions for disease prevention, diagnosis and treatment. Its impact is evident in the development of life-saving drugs, advanced diagnostic tools and personalized therapies. As the field continues to evolve, it holds immense potential to address future healthcare challenges and improve the quality of life for people worldwide. However, careful consideration of ethical, legal and social implications is necessary to ensure that these advancements are used responsibly and equitably.

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