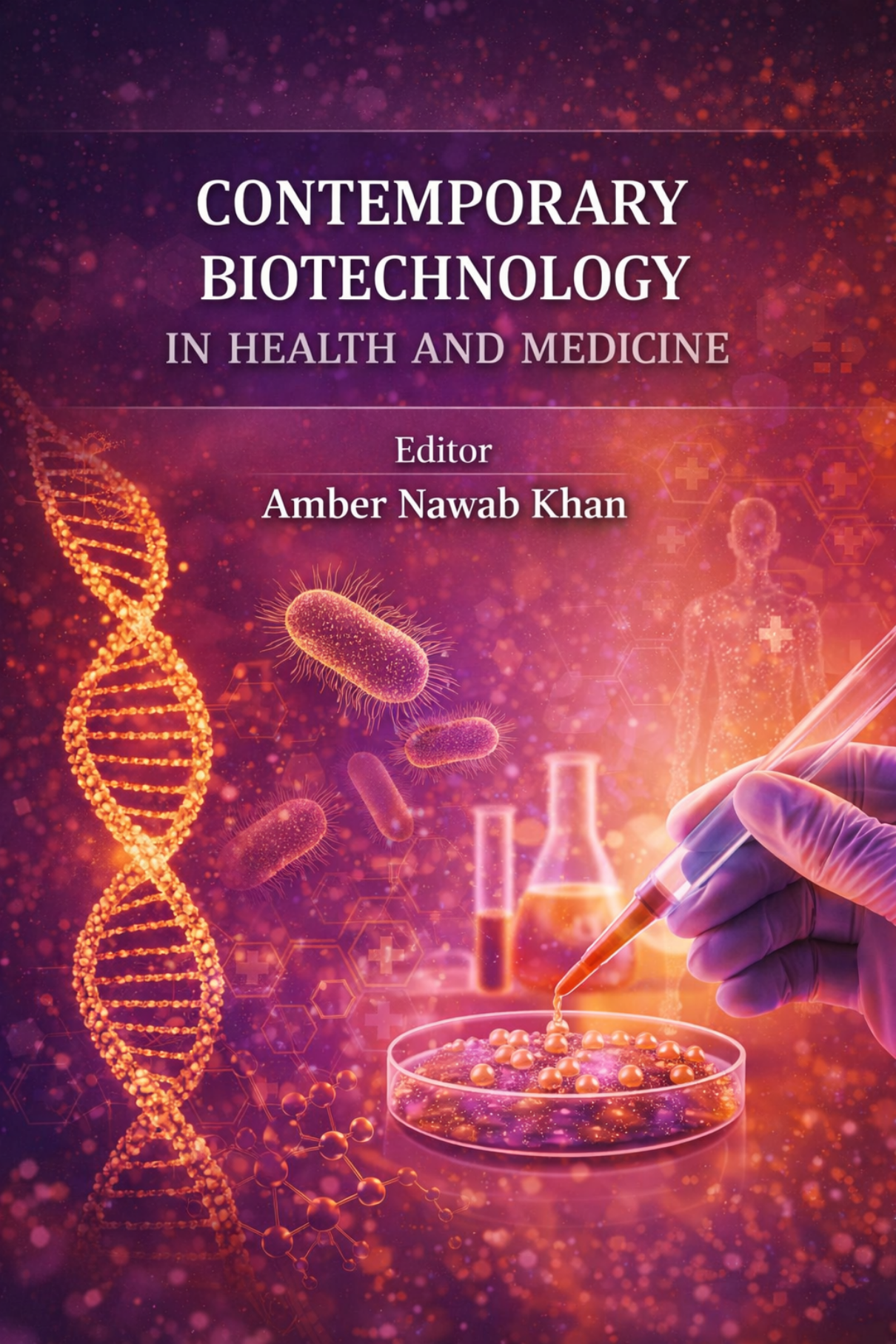
CONTEMPORARY BIOTECHNOLOGY

IN HEALTH AND MEDICINE

Editor

Amber Nawab Khan



CONTEMPORARY BIOTECHNOLOGY IN HEALTH AND MEDICINE- 2025

ISBN: 978-625-93102-1-3

DOI: 10.5281/zenodo.18304841

Edited By

Amber Nawab Khan

January / 2026

İstanbul, Türkiye

Date: 19.01.2026

Halic Publishing House
İstanbul, Türkiye
www.halicyayinevi.com

adopted by Esma AKSAKAL
ISBN: 978-625-93102-1-3

CONTEMPORARY BIOTECHNOLOGY IN HEALTH AND MEDICINE

EDITOR
Amber Nawab Khan

AUTHORS
Asst. Prof. Dr. Vardhana JANAKIRAMAN
Asst. Prof. Dr. Humaira MUZAFFAR
Thaneshwari KAMARAJ RAJESHWARI
Eman JAMEEL
Arslan IFTIKHAR
Fatima ARSHED
Syeda Maham BUKHARI
Rabia Akhtar CHEEMA
Asma HUSSAIN
T.D.G. LIYANAGE
Thushara Indika SAMPATH

TABLE OF CONTENTS

PREFACE

This book presents a thoughtful exploration of scientific progress across three transformative domains: biotechnology, herbal therapeutics, and nanomedicine. Each chapter offers a unique perspective on how innovation, tradition, and technology converge to shape the future of health and medicine.

The opening chapter traces the evolution of biotechnology, from its historical foundations to its current applications and future potential. It sets the stage for understanding how this dynamic field continues to revolutionize industries ranging from agriculture to personalized medicine. The second chapter shifts focus to polycystic ovary syndrome (PCOS), examining the growing body of evidence supporting herbal and plant-based interventions. It highlights the value of integrating traditional knowledge with modern clinical research.

The final chapter delves into the emerging field of nanomedicine, emphasizing its role in advancing drug discovery and targeted therapies. Together, these chapters reflect the power of interdisciplinary research and the promise of science to address complex health challenges through both cutting-edge innovation and time-honored natural remedies.

Editorial Team
January 19, 2026
Türkiye

CHAPTER 1
THE SCOPE OF BIOTECHNOLOGY: PAST, PRESENT, AND FUTURE

[1]Thaneshwari KAMARAJ RAJESHWARI
[2]Asst. Prof. Dr. Vardhana JANAKIRAMAN

[1]Department of Biotechnology, Vels Institute of Science Technology and Advanced Studies, thaneshwari2024@gmail.com, ORCID ID: 0009-0006-5877-4035
[2]Department of Biotechnology, Vels Institute of Science Technology and Advanced Studies, vardhana88@ymail.com, ORCID ID: 0000-0002-8192-0735

INTRODUCTION

The use of systems of biology and living organisms to produce technology and products is known as biotechnology. It is an interdisciplinary field that combines chemistry, engineering, and biology. It has always included customs such as culturing food using yeast. However, modern biotechnology makes use of complex genetic and molecular methods.

The breadth of the field is extremely broad and is frequently classified by color. Red biotechnology is used in medicine to create vaccinations, gene therapies, life-saving medications, and diagnostic instruments. By producing genetically engineered crops that are more robust and nutrient-dense, green biotechnology improves agriculture. Utilizing microorganisms to provide biofuels, bioplastics, and environmentally benign enzymes for production, white biotechnology is applied to industrial operations. Blue biotechnology uses marine life to discover useful chemicals and new medications. Lastly, bioinformatics analyzes the vast amounts of biological data produced by using computational techniques.

During the mid-nineteenth century, a monk by the name of Gregor Mendel modernized this tale (Watson et al., 2013). He would go to the gardens, and through a deliberate and intricate process, would mark the cross-pollination of pea plants. He was deeply fascinated with the characteristics of plants, and with great attention, noted their traits through each generation. His theories proved to be extremely progressive for the time, a time which maybe even ignored this level of progressive thinking. Nevertheless, Mendel's simple theories were the very foundation which modern genetics stand upon as far as unforeseen consequences are concerned and beautiful ideas, the 20th century surely top the list. In the year 1928, a certain British scientist by the name of Alexander Fleming returned from vacation only to find that a mold had contaminated one of his bacterial cultures. He also noticed that instead of throwing the mold out, the scientist noticed that the mold was killing the bacteria. This incredible find led to the discovery of penicillin, the first antibiotic that would save millions of lives through saving from dying because of infections. Biotechnology is of integrated nature This is because living organisms' working problems are through biology and other sciences as well as engineering. This is a collaborative project that depends on many fields.

Biotechnology is connected to basics of life sciences to genetics and molecular biology. Life science is fused with chemistry for the studying and physical manipulation of nucleic acids and proteins, and also molecular biology in order to design new drugs and therapies. The laboratory inventions are taken for large scale production by the aid of bioprocess engineering which is a specialization of engineering that designs systems and facilities for production of biological items like insulin and biofuels. Modern research like the large research outputs from the laboratory depend on computer science and bioinformatics. Biotechnology uses the integration science to put results in useful form for the comprehension of genetic materials and proteins. The collaborative nature is what makes biotechnology powerful. It is a multidisciplinary attempt in medicine, farming, and manufacture (Alberts et al., 2014).

The rationale for this chapter is to provide a comprehensive yet concise overview of biotechnology, integrating its principles, tools, and diverse applications in medicine, agriculture, industry, and environmental management. While biotechnology has been covered in fragmented ways across textbooks and specialized reviews, there remains a need for a consolidated chapter that brings together its fundamental concepts, technological advances, ethical dimensions, and future perspectives. This chapter aims to serve as a resource for students, educators, and researchers by bridging the gap between foundational knowledge and emerging innovations in the field.

1. FUNDAMENTAL PRINCIPLES OF BIOTECHNOLOGY

1.1 Cell And Molecular Biology

The disciplines of Cell and Molecular Biology focus on the anatomy and processes of living organisms on the microscopic level and on the individual cell level, respectively. This domain of study arises from a fundamental framework called the ‘central dogma’ of molecular biology which posits the genetic information thermodynamic flow from DNA molecular folds into as ‘blue let’ and counter transcribed to make ‘sentences’ of RNA, and conversely translated into functional proteins.

The DNA is equated to the principal 'blue print' molecule and from which all forms of life arise due to the 'blue print' being encoded in chemical 'letters' which in addition alters the cell of its morphogenic task and sequentially inter-copies (copies a structural section of) this 'blue print' into smaller, mobile RNA molecule 'copies' which then serves as active 'guides' for the cytoplasmic 'construction sites' called ribosomes. These proteins are molecular 'machines' which, utilize bio-energetics to serve mechanical and structural tasks such as frame work of the living cell. The comprehension of stream line flow of information of a 'bio-computer' by the living cell, serves as fundamental unit of the cell in modern biology and key module in genetics, medicine, and biotechnology.

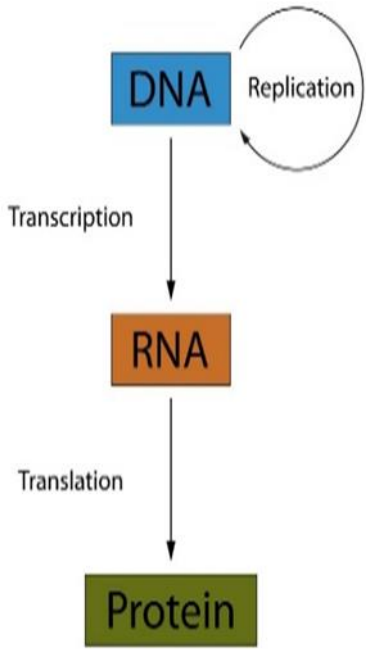


Figure 1. The central dogma of molecular biology

1.2 Recombinant DNA technology and Genetic Engineering

Recombinant DNA technology is a potent technique that generates new DNA sequences by fusing genetic material from various sources. It functions similarly to a molecular cut-and-paste job and is basically genetic engineering.

Scientists used specialized enzymes called “molecular scissors” to cut this gene out of human DNA. They simultaneously break open a tiny, round fragment of bacterial DNA known as a plasmid using the same enzymes. The following stage is the "pasting" of the targeted gene to the plasmid which functions as a molecular "glue" to bind the parts together. This new combination of DNA from two different sources is named recombinant DNA. The final step would be the placement of the recombinant DNA in a host. To illustrate, a bacterium can integrate the new plasmid. The bacterium can reproduce the new gene, along with the new protein, as it copies the new gene, thus yielding a large quantity of the desired protein. One of the most famous instances is the making of human insulin where the gene of human insulin is modified in bacteria, and bacteria become little factories that produce insulin for the injection of diabetics.

1.3 Omics Technologies

"Omics" technologies refer to various scientific methods used to examine biological molecules in a very large, exhaustive manner. The name, resulting from the suffix "-ome" (denoting "the complete set of"), implies studying all of a certain kind of molecule in a cell, tissue, or organism. Rather than focusing on one gene or one protein at a time, omics technologies illustrate an entire system at once, granting researchers a comprehensive view of biological processes.

1.4 Major Types of Omics Technologies

Each of the most famous omics fields identifies one key life molecule as its main focus.

Genomics: This refers to the study of the whole genome of an organism. It supports the discovery of genetic variances, prediction of disease risks, and tracing of the evolutionary timeline.

Transcriptomics: The transcriptome is the subject of this study and the transcriptome refers to the total number of all RNA molecules that arise from the genome at a particular point in time.

Proteomics: The work stands for the study at a large scale of the proteome. Proteins are the "workers" that do most cellular functions; thus, proteomics offers a perfect view of a cell performance at a given time (Venter et al., 2001).

Metabolomics: This method studies the metabolome, which contains all the small-molecule metabolites (such as sugars, amino acids, lipids, etc.) found in a biological sample. Consequently, the study of metabolites becomes a direct indicator of an organism.

Table 1. Comparison of Omics Approaches (Applications and Techniques)

Omics Technology	Core Techniques	Key Applications
Genomics	DNA Sequencing; Gene Editing (e.g., CRISPR).	Diagnosing genetic diseases; identifying disease risks; understanding evolution.
Transcriptomics	RNA Sequencing (RNA-Seq); Microarrays.	Studying gene activity in disease; identifying biomarkers for cancer; understanding cellular response.
Proteomics	Mass Spectrometry; Western Blotting.	Discovering new drug targets; diagnosing diseases; understanding protein function.
Metabolomics	Mass Spectrometry; Nuclear Magnetic Resonance (NMR) Spectroscopy.	Diagnosing metabolic disorders; assessing an individual's response to diet; studying effects of toxins.

2. TOOLS AND TECHNIQUES IN BIOTECHNOLOGY

2.1 Polymerase Chain Reaction (PCR)

PCR (Polymerase Chain Reaction) is a groundbreaking molecular biology method that intentionally creates millions of copies of a particular DNA segment. It is often referred to as "molecular photocopying" and is almost essential when working with really tiny DNA samples (Mullis & Faloona, 1987). The process has three fundamental steps,

Denaturation (94º C): DNA is heated to separate its double strands into single strands.

Annealing (54 ºC): After lowering the temperature, short DNA sequences called primers can attach to their specific target sites on the single strands.

Extension (72º C): After the DNA strands are separated by heat, the DNA polymerase enzyme puts together new strands of DNA, starting at the primers.

Table 2. Types of PCR

Method	Description	Primary Application
Reverse Transcription PCR (RT-PCR)	This method creates a complementary DNA (cDNA) copy from an RNA template using the reverse transcriptase enzyme, which is then amplified using standard PCR.	Discovering gene expression and detecting RNA viruses (e.g., HIV, influenza).
Real-time PCR (qPCR)	This technique allows for the quantification of DNA amplification in real time by using fluorescent markers. This provides a measure of the initial amount of the target DNA.	Gene expression analysis, pathogen quantification, and disease diagnostics.
Multiplex PCR	This technique allows for the simultaneous amplification of multiple DNA targets in a single reaction by using multiple sets of primers that correspond to various targets.	Detecting multiple pathogens or genetic markers at the same time, which is fast and requires less sample material.
Nested PCR	This technique uses two sets of primers for two consecutive PCR reactions. The second set of primers, or "nested" primers, binds within the sequence of the first PCR product, which increases specificity and lowers background amplification.	Improving the specificity of DNA amplification, particularly when the concentration of the target sequence is very low or the background is complex (e.g., a soil sample).

2.2 DNA Sequencing Technologies (Sanger vs. Next-Gen Sequencing)

DNA sequencing refers to methods for determining the order of the nucleotide bases adenine, guanine, cytosine, and thymine in a molecule of DNA. The first DNA sequence was obtained by academic researchers, using laboratories methods based on 2- dimensional chromatography in the early 1970s. By the development of dye-based sequencing method with automated analysis, DNA sequencing has become easier and faster.

Table 3. Sanger Sequencing vs. Next-Generation Sequencing (NGS)

Feature	Sanger Sequencing	Next-Generation Sequencing (NGS)
Throughput	Low. It sequences one DNA fragment at a time.	High. It sequences millions of fragments simultaneously.
Read Length	Long (up to ~1,000 base pairs).	Short (typically 50-600 base pairs, but longer with newer technologies).
Cost	Inexpensive for small projects (e.g., sequencing a single gene).	Inexpensive per base for large projects (e.g., whole genome sequencing), but the initial equipment costs are high.
Speed	Slow. For large projects, it can take days or weeks.	Fast. A whole human genome can be sequenced in a couple of days.
Accuracy	Considered the "gold standard" for high accuracy on short fragments.	Highly accurate for large datasets with sufficient coverage, but the error rate per base can be higher than Sanger.
Data Analysis	Simple and straightforward.	Complex. Requires significant computational power and bioinformatics expertise.
Primary Application	Used for small-scale projects, such as confirming a single gene or a specific mutation, or validating NGS results.	Applied in large-scale projects, such as whole-genome sequencing, exome sequencing, and transcriptome analysis.
Analogy	Like a high-resolution, detailed map of a small area.	Like a satellite overview of the entire world, capturing a broad view.

2.3 CRISPR-Cas and Gene Editing Tools

CRISPR-Cas is a mighty gene-editing tool, which has literally changed the way scientists do molecular biology. Delving Into the Working Principle this revolutionary system features two vital components: The Cas enzyme, frequently Cas9, that provides the function of "scissors" used for DNA cutting. The Guide RNA (gRNA), a simple RNA molecule whose main destination is to match and facilitate the Cas enzyme in reaching the exact DNA sequence that is to be cut (Jinek et al., 2012).

The scientists, in turn, can take control over this repair process and transform it to be in their favor: one way is letting the cell fix the break in an incomplete manner (thus creating a "knockout") and so the gene becomes inactive; another way is by giving a new DNA sequence as a template for the cells to use and in that way a mutation gets corrected or a new gene is inserted. These features of CRISPR-Cas have been the spearhead of the present-day genetic research regardless of the amazing possibilities of other gene-editing methods. According to the development of scientific research, the technology of CRISPR-Cas and their derivatives, such as base editing and priming editing, are also kept evolving making them more refined.

2.4 Cell and Tissue Culture Techniques

Cell and tissue culture refer to processes of growing living cells, tissues, or organs artificially outside their normal habitat but in an environment that is both controlled and standardized. Such methods are the very base of the whole contemporary biological research and medicine as they allow the scientists to conduct their experiments with biomaterials thus providing much-needed materials.

2.4.1 Cell Culture Techniques

One of the most common practices in cell culture is single cells or a population of cells to be grown, most of the time, in a petri dish or flask. For this method to be successful the use of a special culture medium is necessary which is expected to provide all the essential nutrients, growth factors and also serve as a buffer to keep a constant pH. Some of the main techniques are as follows:

Aseptic Technique

Keeping a sterile environment is very important in order to avoid contamination by microorganisms such as bacteria and fungi. In this respect, a sterile air supply from a laminar flow hood is always used to completely eliminate contaminations.

Subculturing (or Passaging)

Cells, as they grow and get vigorous, will at some time wrap the entire surface of the culture vessel, a condition which is termed as confluency. To avoid crowding and ensure that the culture remains healthy, some cells are removed and put in a new container along with fresh media.

Cryopreservation

A method designed for the long-term storage of the cells when they are frozen at very low temperatures (usually in liquid nitrogen) so that they can be used again at a later time without losing their viability.

2.4.2 Tissue Culture and Its Applications

Tissue culture is often referred to as in vitro growth of tissue fragments or whole organs, thus, it is a general term for these processes. The idea is to keep the tissue original form and function. The use of this technology can be seen in following areas:

Plant Tissue Culture

It is a technique used for duplicating plants from a very small section of tissue, micropropagation.

Animal Tissue Culture

The process of implanting diseases into animals and culturing animal cells in laboratories is instrumental in the development of biomedicine. It is very helpful in tissue engineering for making artificial organs and tissues for transplantation.

2.5 Bioreactors and Fermentation Processes

Bioreactors are large containers or chambers, which function to sustain the growth of living beings, be it microorganisms or plant and animal cells, in a controlled environment so as to obtain a certain product. These are the center of almost all biotech processes that provide ideal conditions for growth, among which temperature, pH, oxygen supply, and nutrients.

Bioreactor is often synonymous with a fermenter; however, the former defines, in general, the cultivation processes of bacteria, yeast, or fungi, while the latter refers to fermentation only, that is, a metabolic process that changes a substrate (e.g., sugar) into a product (e.g., alcohol or acid).

2.5.1 Types and Applications

There are different Bioreactors and each one serves a different purpose Types of Bioreactors and Their Applications.

Stirred-tank bioreactors are those with the most common design and a central impeller through which the culture is mixed and aerate. They can be a) general and the used for large scale production of i) antibiotics, ii) enzymes, and iii) other biopharmaceuticals e.g.

Photobioreactors are lit by lights, and their purpose is the cultivation of the photosynthetic organisms, the most typical example of which are algae, whose uses include biofuel production and wastewater treatment. The uses of bioreactors and fermentation cover an extensive field and are very important for lots of industries. For example, a list of products made using these methods can be as follows:

Pharmaceuticals. Vaccines, antibiotics, insulin, and therapeutic proteins. Food and Beverages. Beer, wine, yogurt, cheese, and the like. Citric acid.

Biofuels: Ethanol generated from corn or sugarcane and biodiesel derived from algae.

Chemicals: Industrial enzymes, organic acids, and bioplastics.

Using bioreactors, the production of these products is made in a very effective manner and on a large scale. Through this way, they are able to turn what were originally small-scale, traditional processes, into highly controlled, modern industrial operations

2.6 Bioinformatics and Computational Tools

Bioinformatics is a multidisciplinary subject that uses biology, computer science, and statistics to manage, analyze, and interpret huge biological data sets. This area is necessary to bring clarity to the enormous amounts of data generated by modern technologies such as Next-Generation Sequencing (Kumar & Singh, 2020).

The use of computational tools in bioinformatics is a mainstay; they allow researchers to get hold of, analyze, and present through figures the intricate data, thereby, revealing the meaningful biological insights that would otherwise be hard to detect if done manually.

2.6.1 Common Computational Tools

The field of bioinformatics utilizes different software, algorithms, and databases to carry out its analysis. The most common tools and their possible uses may be those mentioned below.

Sequence Alignment Tools

These tools align and find the similarities of DNA, RNA, or protein sequences. The identified similarities may suggest the functions, the structures, or the evolutionary relationship of the sequences. As an illustration to this, BLAST (Basic Local Alignment Search Tool) is an essential algorithm that is employed to carry out sequence similarity searches against large databases such as GenBank. Besides, ClustalW is a main tool that is used in multiple sequence alignment which is helpful in building the evolutionary trees.

Genome Assembly and Annotation Software

The whole genome is represented in millions of small fragments when it is sequenced. So as to "assemble" or "re-construct," in other words, "merge" the genome or the sequence adjacent fragments back together, computational tools such as SPAdes or Velvet are used. Subsequently, tools which are used for genome annotation means that they identify and mark the regions of genes, regulatory regions, and other important signs in the genome in addition to locating them.

Protein Structure Prediction

The 3D structure of a protein is very important in determining the functions of the protein. Computations can be greatly instrumental in doing the task of predicting the structure of proteins directly from the amino acid chains.

A few years ago, the likes of AlphaFold, the promoter of immense deep learning methods, have completely changed the prediction of protein structure to be very close to the experimental one, opening the door for huge pharmaceutical advancements and greatly accelerated molecular biology research.

Databases

Bioinformatics relies on numerous publicly available databases that store vast amounts of biological information. A few examples could be GenBank (for DNA and RNA sequences), the Protein Data Bank (PDB) (for 3D protein structures), and UniProt (for protein sequence and function information). The role of these databases is the basis of the previous statement. They constitute the critical support in comparative analysis and data-driven research.

3. APPLICATIONS OF BIOTECHNOLOGY

3.1 Medical Biotechnology

Vaccines (traditional and recombinant)

Vaccinations operate by teaching the body immune system to identify and eliminate the dangers before they even get to cause any disorders. The antigen introduced, which is a thing that evokes an immune reaction, is the body. Thereafter the immune system manufactures antibodies and memory cells which are capable of rapidly annihilating the intruder if at some point it invades the organism again.

Traditional Vaccines

Traditional vaccines consist of whole pathogens that have been either disabled or completely done away. Live-attenuated vaccines comprise a weakened variant of the live pathogen that is unable to cause disease yet can still replicate in the body. Such replication simulates a natural infection, hence a strong and long-lasting immune response, usually only one or two doses being sufficient. Some of these are the vaccines for measles, mumps, and rubella (MMR).

Recombinant Vaccines

Recombinant vaccines are the new generation vaccines that employ genetic modification techniques for creating specific antigens in a lab setting. The scientists refrain from using the complete pathogen and instead define the gene enabling the pathogen to make the key protein (antigen).

Monoclonal Antibodies and Therapeutics

Monoclonal antibodies (mAbs) are synthetic proteins that resemble the body natural antibodies. They are engineered to latch onto one particular molecule, or antigen, which is usually a part of the surface of harmful cells such as cancer cells or pathogens. The phrase "monoclonal" means that they are all identical copies (clones) of one parent antibody, hence they can only bind to one, specific target. mAb-based therapeutics are the principle of current medical practice, because mAbs are capable of curing various diseases with the very high precision and less side effects compared to the reliances on treatment such as chemotherapy. They can perform their functions in a variety of ways:

Braking Signals: In certain cases, some mAbs might get attached to cancer cells by receptors and thus prevent the connections. The widely known example is Trastuzumab, which helps by stopping a protein that encourages growth type.

Immune System Activation: Certain mAbs are like flags which, when present on a target of a diseased cell, allow the body immune system to spot, attack, and destroy the marked cell.

Drug Delivery on the Target: There are also cases of "conjugated" mAbs where a poisonous agent such as a chemo drug or a radioactive particle is linked to the mAb.

Neutralizing Pathogens: In the case of infections, mAbs would attach themselves to viruses or toxins and neutralize them so that they cannot enter cells and cause damage. Besides, severe cases of COVID-19 are mAbs a good example of their application in infectious diseases.

Gene Therapy

Gene therapy is a treatment method that changes or treats a person gene to cure a disease. It does not use drugs or surgery to ease the symptoms, but directly targets the origin of genetic diseases by dealing with the defective gene one. Gene therapy is very effective to cure a large variety of inherited diseases such as cystic fibrosis and hemophilia, that is good news for patients suffering from those diseases. In addition, gene therapy will be quitean advantage for cases of cancers, infectious diseases, and other conditions. There are two ways of delivering the vector:

Ex vivo: cells are taken out of the patient, changed in a lab, and then put back into the body.

In vivo: the vector is directly injected into the patient body to reach the targeted cells.

Personalized Medicine and Pharmacogenics

Personalized medicine, or precision medicine, is basically a healthcare system which adjusts the treatment of a patient in accordance with his/her unique features such as genes, surroundings, and lifestyle. The traditional "one-size-fits-all" model is opposite to this, which in most cases is ineffective for some patients and gives them severe side effects along with the rest of the treatment. The main feature of personalized medicine is still pharmacogenomics, a field which surveys the affiliations between a human being gene and the reaction of drugs. Physicians utilize the genetic makeup of patients to implement pharmacogenomics in the following: Drug that is the most effective for the patient to take. This model is already implemented in different departments such as oncology (choosing the best chemotherapy for the patient tumor), psychiatry (deciding the correct antidepressant), and cardiology (securing the right dose of blood thinners including warfarin). Personalized medicine is on its way to making healthcare not only reactive but also preventive, predictive, and entirely individualized one.

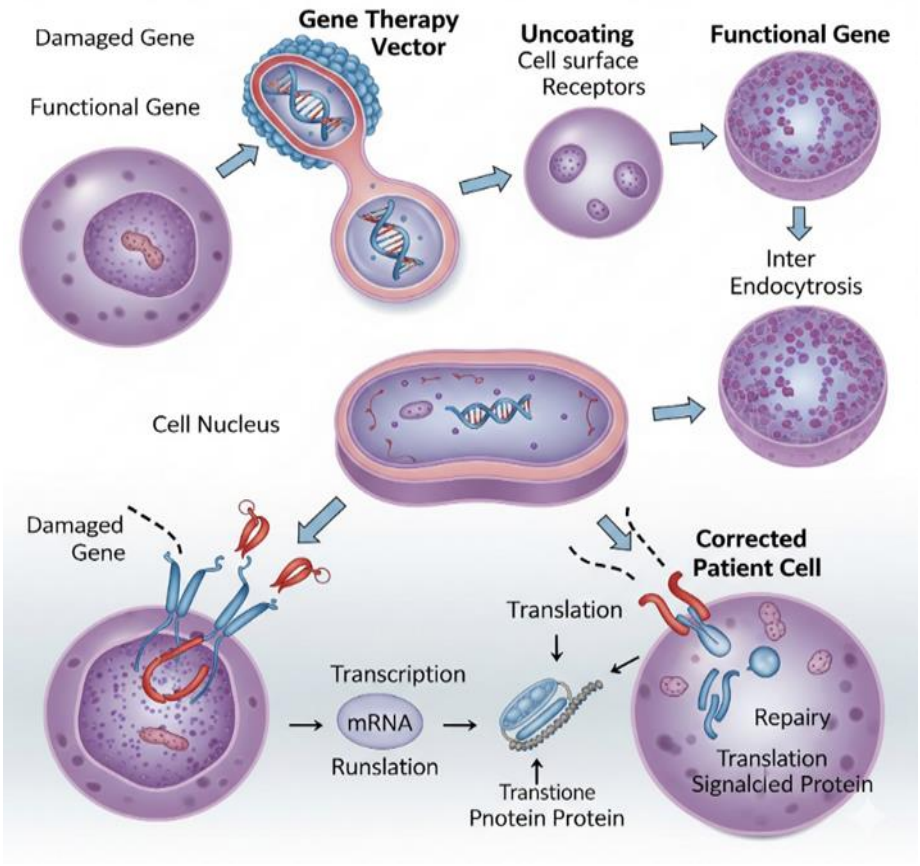


Figure 2. Mechanism of Gene Therapy

4. AGRICULTURAL BIOTECHNOLOGY

4.1 Genetically Modified (GM) Crops

Genetically modified (GM) crops are plants that have had their DNA radically changed through genetic engineering so that they have completely new and desirable traits that do not exist naturally. The very first step in the process is to find the gene of one organism that will bring a definite advantage, for example, resistance to pests or tolerance to drought. After that, the scientists will make a copy of this gene and put it in the DNA of a plant which is a crop. One of the methods that are used is a bacterium called Agrobacterium tumefaciens which transfers the gene into the cells of the plant.

Insect Resistance

The gene of the bacterium Bacillus thuringiensis (Bt) can be taken from the bacterium and inserted into the DNA of crops like corn and cotton.

Herbicide Tolerance

Genetically modified techniques can be used to turn products like soybeans and canola into resistant crops against different herbicides. Other uses may include the development of nutrient-enriched food-stuffs, such as "Golden Rice", genetically modified rice to produce beta-carotene as a means of fighting vitamin A deficiency (James, 2018; Singh et al., 2011).

Pest and Disease Resistance

Pest and disease resistance in plants refers to their capabilities to fight off the invasion by pests and diseases caused by fungi, bacteria, or viruses. Besides their naturally occurring defenses, plants are equipped with a sophisticated immune system that can be switched on when infection takes place.

Physical Barriers: Plants carry inherently protective features such as a waxy cuticle on leaves or sturdy cell walls that serve as a protective layer against invaders.

Chemical Defenses: The organisms can generate acids, enzymes, or come sticky that can attract or kill the intruders and pathogens.

Genetic Resistance: Plants have some particular genes known as R-genes (Resistance genes) that can identify the components of pathogens.

Biofertilizers and Biopesticides

Biofertilizers are one the best would be source of the living microorganisms that make soil to be compromised 100% for plants through their can supplymently 100% of the natures and even more than that they obtain nature products like nitrogen fixation (e.g., Rhizobium bacteria) and phosphate solubilization to single out the synthetic fertilizers line. They also refurbish soil. Biopesticides are products derived from natural substances or organisms which are used against the pests and diseases.

They may be tiny living creatures (such as Bacillus thuringiensis bacteria, which kills specific insect larvae) or completely natural plant extracts.

Plant Tissue Culture and Micropropagation

Plant tissue culture refers to the procedure of developing isolated plant cells, tissues, or even organs in a non- contaminated, synthetic medium. It involves the usage of totipotency-the feature of single investigation and to yield a big volume of plants. Micropropagation is the one, which can be referred to as the general concept of plant tissue culture as a specific example. Compared to tissue culture which is an encompassing term for the growth of plant cells in the laboratory, micropropagation is a particular method for the duplication of plants on a large scale.

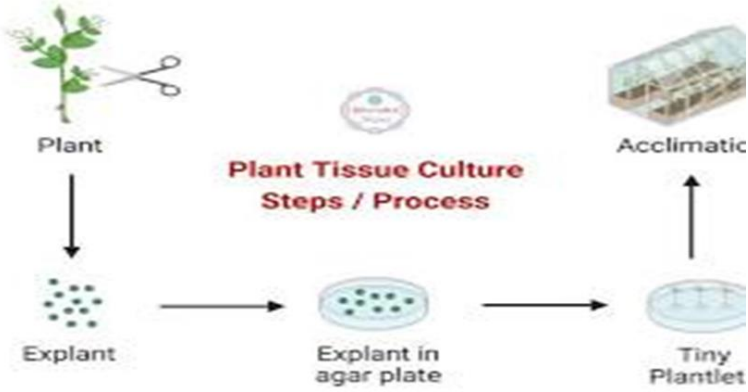


Figure 3. Flowchart of Plant Tissue Culture Process

5. INDUSTRIAL BIOTECHNOLOGY

Detergents

One of the major application fields of enzymes is modern detergents that have been made more effective to remove the most stubborn stains when used together with less energy. Proteases degrade the protein part of the stain to put it into that blood, grass, and eggs that may stick to you. Lipases attack fats and oily nature that might have come from the food or the beauty department to the textile and made the stain.

Amylases help to break starch contained in pasta or potato residues. Cellulases help cotton cleansers to detach the tiny fibers which make pilling and therefore the color and softness of washable is rejuvenated (Demain & Adrio, 2008).

Food Industry

The major field of enzyme application is the needs of food textures, flavors, and shelf lives that are met through enzyme usage. Moreover, enzymes are also used to create new food products. Amylases convert starch present in baking and brewing into glucose that is the reason for bread texture improvement and the supply of yeast fermentation. Proteases help the process of cheese formation by releasing the protein fraction and are also involved in the tenderization of meat in the meat industry. Lactases are the tools used to get rid of lactose from milk-based products and create lactose-free ones. Lactose is turned into simple sugars by the action of these enzymes.

Textiles

The textile industry uses enzymes to reduce the impact of their chemical treatment on the environment without compromising the product quality in many processing steps. Amylases are commonly used in desizing operations to remove the starch-based coating that was applied on the yarn before weaving. Cellulases are used in biopolishing to give fabrics a smoother, softer surface and a brighter appearance by the removal of surface fibers. Laccases and peroxidases are used for the sustainable bleaching of the environment-friendly textile. These enzymatic operations cause less demand for water and energy and less fabric damage.

Production of Biofuels and Biopolymers

Biofuels

Biofuels like bioethanol and biodiesel are made out of biomass that consists of corn, sugarcane, or algae. Biodiesel is made by a chemical procedure known as transesterification whereby vegetable oils or animal fats are converted to biodiesel. These biofuels are used to reduce carbon emissions which is the main source of global warming.

Biopolymers

Biopolymers or bioplastics are compostable polymers that are derived from renewable resources such as cornstarch, sugarcane, or cellulose. Microbes can be customized to transform these plant-based sugars into polymers, which are then used to manufacture green plastics and packaging. These materials help reduce dependence on fossil fuels and lower overall carbon emissions. They also decompose more easily in natural environments, minimizing long-term pollution. Advances in biotechnology continue to improve their durability and functionality for various industrial applications. As global demand for sustainable materials grows, bioplastics are expected to play an increasingly important role in the circular economy.

Fermentation in Food and Beverage Industry

Fermentation is a metabolic process that basically changes carbohydrates (sugars) into alcohol, acids, or gases with the help of microorganisms like bacteria, yeast, or fungi. This process has been used for centuries in food preservation and the production of beverages. It also enhances the flavor, texture, and nutritional value of many foods. In industrial settings, fermentation is essential for producing antibiotics, biofuels, and various biochemicals. As biotechnology advances, fermentation continues to play a crucial role in sustainable manufacturing and environmental solutions.

Food

The food industry heavily relies on fermentation to produce various products. The use of bacteria to ferment milk is the process of producing yogurt, cheese.

Beverages

Fermentation watershed is the way through which all alcoholic beverages are made. Yeast eats the sugars in fruits (wine) or grains (beer), and turns them into ethanol and carbon dioxide.

Table 4. Industrial Applications of Microbial Enzymes

Industry	Enzyme(s)	Function/Application
Detergents	Proteases, Lipases, Amylases, Cellulases	Break down protein, fat, starch, and cellulose-based stains; improve cleaning efficiency in cold water; prevent fabric pilling.
Food & Beverage	Amylases, Proteases, Lactases, Pectinases	Convert starch to sugar (baking, brewing); curdle milk (cheesemaking); tenderize meat; produce lactose-free products; clarify fruit juices.
Textiles	Amylases, Cellulases, Laccases	Desizing (remove starch from fabric); bio-polishing (smooth fabric surface); environmentally friendly bleaching and dyeing.
Biofuels	Cellulases, Amylases	Break down biomass (cellulose, starch) into fermentable sugars for ethanol production.
Paper & Pulp	Xylanases, Laccases	Bleach wood pulp to produce paper; improve paper quality and reduce the need for harsh chemicals.

6. ENVIRONMENTAL BIOTECHNOLOGY

Bioremediation (oil spills, heavy metals)

Bioremediation is the use of living organisms, mainly microbes, to reverse the damage caused by pollution to the natural environment. It is a natural and earth-friendly way to get rid of the dirtied lands.

Oil Spills

Microbes like certain bacteria that can break down the hydrocarbons found in oil. They do not waste the oil but rather make it into a new product which is consisted of water and carbon dioxide, both of which are non-toxic to human beings and animals. This natural process makes them valuable tools in cleaning up oil spills and contaminated environments. They help restore ecosystems more quickly by reducing harmful pollutants.

Heavy Metals

To absorb and store heavy metals (like mercury or lead) from the soil or water, the aid of some bacteria and plants is taken.

Biosensors for Pollution Detection

Biosensors are devices that are analytical in nature and combine a living component with a physicochemical unit to sense and quantify a target substance. The structure of a biosensor is essentially two parts:

A bio-element (for example, enzymes, antibodies, or microorganisms) that recognizes a pollutant specifically.

A transducer that changes a biological reaction into a detectable signal, such as an electrical current, light emission, or color change. This technology is indispensable for environmental monitoring in real time and also for public health protection.

These sensors provide high specificity and sensitivity toward the target substance. They also enable rapid response times, allowing real-time analysis. In this way, they play a crucial role in the early detection of environmental risks and the monitoring of potential public health threats.

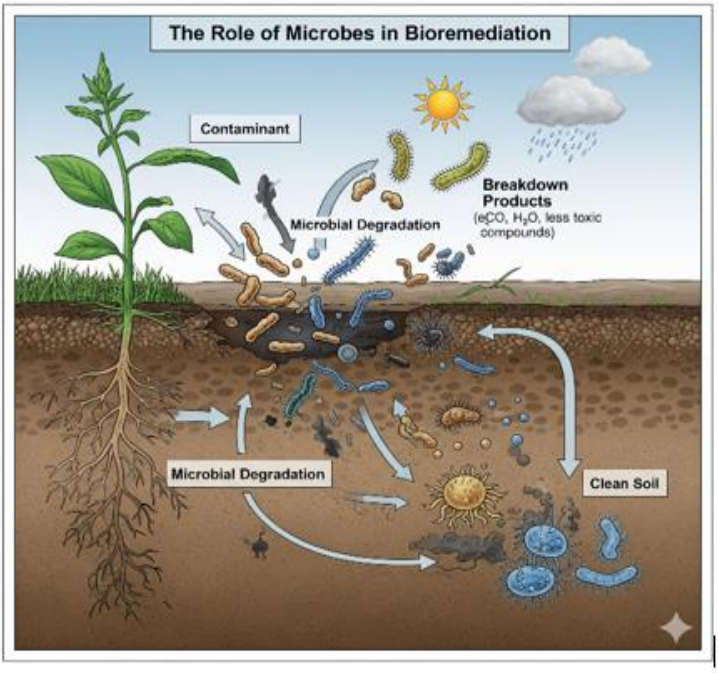


Figure 4. Role of Microbes in Bioremediation

7. EMERGING FIELDS

7.1 Marine Biotechnology

Marine biotechnology, known as "blue biotechnology," is an adventurous journey into the bountiful biological resources of the seas for the creation of new products and technologies.

Applications

Enzymes: Marine bacteria and algae create innovative enzymes that keep their activity at low temperatures.

Biomaterials: Materials like chitosan derived from crab shells are utilized in healthcare fields, for instance, as wound dressings and formulations for controlled release of drugs.

Pharmaceuticals: Marine is an almost inexhaustible treasure house of substances that can bring about therapeutic benefits.

Biofuels: The picture of microalgae, which are able to multiply very fast, is being drawn as a source of biofuels, which is put forward as a choice of renewable energy.

7.2 Nanobiotechnology

Nanobiotechnology is an interdisciplinory field that merges nanotechnology (the changing of the structure of matter at an atomic level) with biology. The main unit of focus is the use of extremely small devices and materials, which are generally considered as those with dimensions of 1 to 100 nanometers, and the exploitation of these for interaction with living systems.

Applications

Drug Delivery: We can design nanoparticles in such a way that they carry drugs directly to the infected cells for instance, tumors(Kumar & Singh, 2020).

Diagnostics: Nanosensors are equipped to detect the presence of biomarkers for diseases with a very high sensitivity level, thus allowing the diagnosis to be made earlier and more accurate.

Tissue Engineering: We can use nanomaterials as the basic structure to support the development of the new tissues and organs.

Gene Therapy: Nanoparticles are capable of transporting the therapeutic genes to the target cells thereby providing an alternative that is non-viral to the traditional vectors.

7.3 Ethical, Legal, and Social Issues (ELSI)

Bioethics and Human Genome Editing

Bioethics is a branch of knowledge that deals with the ethical, social, and legal issues related to the progress in biology and medicine. It is a system for the consideration of the moral aspects of such inventions as editing the human genome. These concerns include:

Safety: The danger of an unintentional "off-target" effect or the absence of long-term data.

Equity: The possibility of a "genetic divide" where only the rich can afford genetic enhancements.

Germline Editing: The question of whether it is right to make changes in the human genome that can be inherited by subsequent generations.

Consent: The problem of consent to those who will be permanently changed, but without their knowledge.

7.4 Intellectual Property Rights And Patenting İn Biotechnology

Intellectual Property Rights (IPRs) in biotechnology are the legal rights that are given to the creators to protect their works and discoveries. Through these rights, companies are able to have total control over the inventions for a limited period during which no one else is allowed to make, use, or sell them without the consent of the owners.

7.5 Patenting in Biotechnology

Patent is the most important and decisive form of IPR in the field of biotechnology. The invention has to satisfy the three main characteristics in order to be patented:

Novelty: The invention should be new and no one should have the access to the description of it before.

Inventive Step: The invention should be understandable by a person who has a background in the field.

Industrial Applicability: The invention should have a practical use.

Public Perception and Controversies

Public perception of biotechnology is usually a bit confusing, and in some cases, there are controversies that arise around particular applications. On the one hand, a lot of people consider the use of biotech as a solution to numerous problems such as diseases and food shortages. On the other hand, these people also express their fear of the technology.

Key Controversies

Genetically Modified Organisms (GMOs): The issue of GMOs is at the center of most debates. The public fears the consumption of genetically modified foods and their possible impact on the biological variety, along with the scare of "out of control science" by altering nature.

Human Genome Editing: The use of such tools as CRISPR-Cas9 for gene editing in human has opened the door for ethical questions of enormous magnitudes to be raised (Jinek et al., 2012).

One of the most talked-about issues is "designer babies"editing embryos to gain non-therapeutic traits which is the main reason for such a hot debate, along with the concern over the possibility to create a new kind of social inequality based on genetics.

8. FUTURE PERSPECTIVES OF BIOTECHNOLOGY

Regenerative Medicine and Stem Cell Therapy

Regenerative medicine, on the other hand, is the medical practice to develop procedures that can restore, substitute, or create new healthy tissues and organs. One of the major elements in regenerative medicine is stem cell treatment. Stem cells are the most perfect cells in the body which possess two main characteristics: firstly, they can replicate themselves (create more copies of themselves) and secondly, they can become different (specialize) cells.

These unique abilities make stem cells essential for repairing damaged tissues. They can be directed to replace cells lost due to injury, disease, or aging.

In addition, advances in biomaterials and tissue engineering further enhance the effectiveness of stem cell–based therapies. Together, these developments hold great promise for treating conditions that were once considered irreversible.

AI and Machine Learning in Biotechnology

AI (Artificial Intelligence) and ML (Machine Learning) have revolutioned biomedical technology through the efficient handling of data which has sped up the process of scientific breakthrough.

Key Applications

Drug Discovery: It is possible for AI models to foresee the most feasible drug candidates thus limiting the time in which new therapies are developed. The procedure they use is to skim through the numerous molecules to find the ones that might work against a particular illness.

Genomics: ML algorithms are practical tools along with human experts to deal with multi-dimensional genetic data which can come from various sources and can be extremely complicated.

Protein Engineering: With the help of AI, it is possible to foresee the native state of a protein molecule from the primary structure with almost no errors.

Diagnostics: AI-enabled tools can efficiently perform tasks such as medical imaging and radiography etc. at a higher accuracy and with much less time than human doctors can thus lowering the chance of errors in diagnosis and may facilitate early diagnosis of the conditions.

Role of biotechnology in achieving Sustainable Development Goals (SDGs)

Biotechnology is the key driver to the implementation of the Sustainable Development Goal as well as an innovation leader across the crucial areas of food security, health, and environmental protection.

Direct Contributions to SDGs

SDG 2: Zero Hunger

It opens a path for biofortification whereby the growth nutrition level is even higher to eliminate malnutrition.

SDG 3: Good Health and Well-being

Biotechnological diagnostics can quickly locate and trace infections that can harm population health and subsequently public health all around the globe.

SDG 6: Clean Water and Sanitation

Bioremediation is cleanup with microbial helpers as they eat all the harmful stuff like mercury coming in ground water, thus making it safe again for human usage or for throwing into nature without causing damage. This method is considered environmentally friendly because it relies on natural biological processes. It can be applied to soil, water, and even air environments affected by pollution. As research advances, bioremediation techniques are becoming more efficient and widely used in environmental restoration efforts.

SDG 7: Affordable and Clean Energy

Magic of biotechnology is the source of renewable energy technology.

SDG 12: Responsible Consumption and Production

Bioplastics and biomaterials are derived from plants and other renewable sources rather than using existing plastic which makes them scrap and pollutant-free. They help reduce environmental waste by breaking down more easily than conventional plastics. Their production also lowers dependence on fossil fuels and decreases carbon emissions. As technology advances, these materials are becoming stronger and more versatile for everyday use.

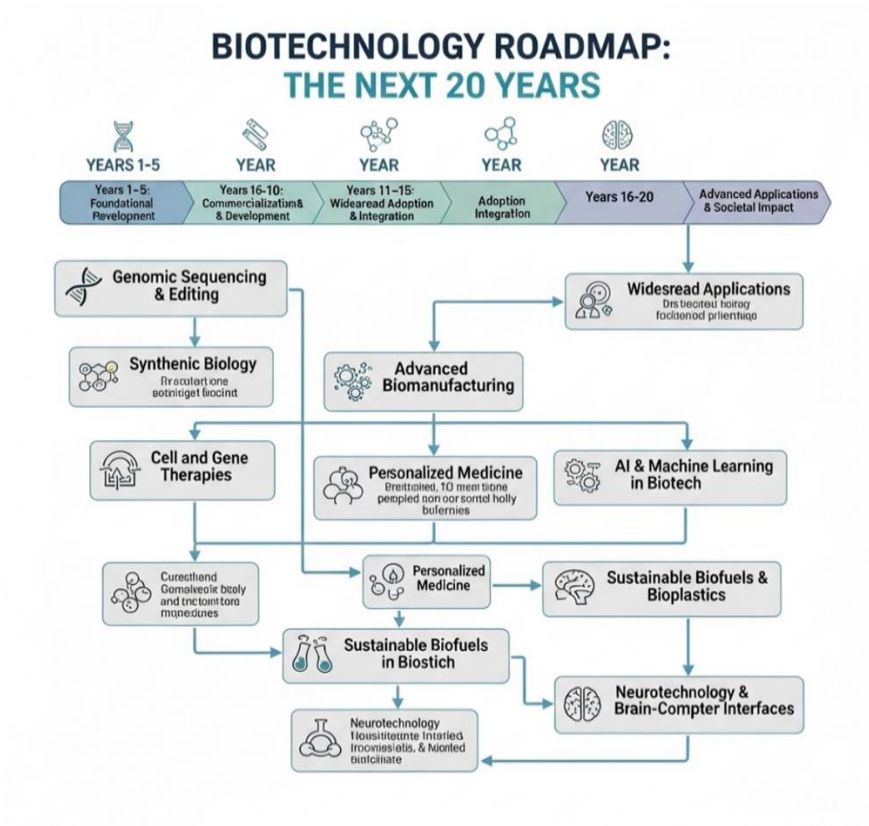


Figure 5. Biotechnology Roadmap for the Next 20 Years

CONCLUSION

Biotechnology is the marvel of technology that touches almost all the areas of human life and the earth but it still has to overcome quite a few hurdles. The applications come from the success achieved in the manipulation of living organisms for the purposes intended. In health, it has resulted in the discovery of vaccines and a number of therapeutic methods, namely monoclonal antibodies, and gene therapy. The advent of genetically modified crops in agriculture has significantly increased yield and crop resistance. Enzymes are the areas that seek the change with the use of enzymes like detergents and food processing where they seek to increase efficiency and simultaneously reduce carbon footprint in the atmosphere. Unfortunately, the opportunities of biotechnological applications come with a series of obstacles.

One of the big barriers is the towering cost and time-consuming regulatory procedures for new biotech products especially in health. Technology progress is very often accompanied by the rise of ethical concerns and this is the case with human genome editing and the possibilities of "designer babies." Public view may be a tough competitor to face in the battle arena, since the lack of knowledge and media sensationalism often fuel mistrust and controversy around issues like GMOs. Moreover, these issues certainly do not stop at patents and intellectual property as they further complicate the field with the result that ownership disputes lead to cancellation of research and product development.

Biotechnology has a bright future no doubt and we can notice a few main trends that define it. The integration of biotechnological methods with AI and machine learning is one of the most effective ways to fast-track drug trials, genomics-based personalized treatment, and bioinformatics and hence the cutting-edge research and clinical trial can be quickly analyzed by data mining of huge biological data sets which leads to the discovery of new innate biological properties. We can only expect synthetic biology to grow by leaps and bounds in the future as that prompts us to engineer completely novel living systems for a variety of usages like producing green materials or generating clean energy.

The promises of the biotechnological field will open up quite a lot of channels with the decrease in prices of the likes of DNA sequencing and CRISPR-Cas9 and this is where more researchers from different locations and smaller companies will be able to use such technologies. The concentration will shift more towards the issue of making the earth and human life more environmentally friendly, taking the advantage of bioremediation, biofuel, etc. as necessary solutions to the problem of climate change.

REFERENCES

Alberts, B., Johnson, A., Lewis, J., Morgan, D., Raff, M., Roberts, K., & Walter, P. (2014). Molecular biology of the cell (6th ed.). Garland Science.

Brown, T. A. (2017). Genomes 4. Garland Science.

Dale, J. W., & von Schantz, M. (2007). From genes to genomes: Concepts and applications of DNA technology (2nd ed.). Wiley.

Demain, A. L., & Adrio, J. L. (2008). Contributions of modern biotechnology to sustainable development. Microbial Biotechnology, 1(4), 283–302. https://doi.org/10.1111/j.1751-7915.2008.00028.x

James, C. (2018). Global status of commercialized biotech/GM crops: 2018 (ISAAA Brief No. 54). International Service for the Acquisition of Agri-Biotech Applications.

Jinek, M., Chylinski, K., Fonfara, I., Hauer, M., Doudna, J. A., & Charpentier, E. (2012). A programmable dual-RNA–guided DNA endonuclease in adaptive bacterial immunity. Science, 337(6096), 816–821. https://doi.org/10.1126/science.1225829

Krebs, J. E., Goldstein, E. S., & Kilpatrick, S. T. (2018). Lewin's Genes XII. Jones & Bartlett Learning.

Kumar, A., & Singh, R. (2020). Bioinformatics in life and environmental sciences: A review. Journal of Applied Biology & Biotechnology, 8(1), 1–10. https://doi.org/10.7324/JABB.2020.80101

Lodish, H., Berk, A., & Kaiser, C. A. (2021). Molecular cell biology (9th ed.). W. H. Freeman and Company.

Mullis, K., & Faloona, F. (1987). Specific synthesis of DNA in vitro via a polymerase-catalyzed chain reaction. Methods in Enzymology, 155, 335–350. https://doi.org/10.1016/0076-6879(87)55023-6

Primrose, S. B., & Twyman, R. M. (2006). Principles of gene manipulation and genomics (7th ed.). Blackwell Publishing.

Sanger, F., Nicklen, S., & Coulson, A. R. (1977). DNA sequencing with chain-terminating inhibitors. Proceedings of the National Academy of Sciences, 74(12), 5463–5467. https://doi.org/10.1073/pnas.74.12.5463

Satyanarayana, U. (2008). Biotechnology. Books and Allied (P) Ltd.

Singh, J. S., Abhilash, P. C., Singh, H. B., Singh, R. P., & Singh, D. P. (2011). Genetically engineered crops: Prospects and environmental impacts. Ecological Economics, 70(6), 1109–1116.

Venter, J. C., Adams, M. D., Myers, E. W., et al. (2001). The sequence of the human genome. Science, 291(5507), 1304–1351.

Watson, J. D., Baker, T. A., Bell, S. P. (2018). Molecular biology of the gene (7th ed.). Pearson.

Watson, J. D., Baker, T. A., Bell, S. P., Gann, A., Levine, M., & Losick, R. (2013). Molecular biology of the gene (7th ed.). Pearson.

Watson, J. D., Caudy, A. A., & Myers, R. M. (2007). Recombinant DNA: Genes and genomes – A short course (3rd ed.). W. H. Freeman and Company.

CHAPTER 2
HERBAL AND PLANT-BASED INTERVENTIONS IN POLYCYSTIC OVARY SYNDROME: EVIDENCE-BASED PERSPECTIVES

[1]Eman JAMEEL
[2]Asst. Prof. Dr. Humaira MUZAFFAR
[3]Arslan IFTIKHAR
[4]Fatima ARSHED
[5]Syeda Maham BUKHARI
[6]Rabia Akhtar CHEEMA
[7]Asma HUSSAIN

[1]Department of Physiology, Government College University
[2]Department of Physiology, Government College University, drhumairamuzaffar@gcuf.edu.pk, ORCID ID: 0000-0003-2172-8474
[3]Department of Physiology, Government College University
[4]Department of Physiology, Government College University
[5]Department of Physiology, Government College University
[6]Department of Physiology, Government College University
[7]Department of Physiology, Government College University

INTRODUCTION

The term polycystic ovarian syndrome (PCOS) refers to the numerous growth-arrested follicles that are frequently observed in women's larger ovaries. This condition is characterized by irregular or nonexistent menstrual cycles, hyperandrogenism, and associated metabolic and psychological aftereffects.

Infertility, hirsutism, insulin resistance, acne, weight gain, irregular menstruation, ovarian cysts, androgen development are only a few of the clinical symptoms that are associated with PCOS. In PCOS, an overproduction of ovarian steroids is often observed, linked with impaired insulin sensitivity, along with disturbances in gonadotropin release, particularly in follicle-stimulating hormone (FSH) and luteinizing hormone (LH) levels.A severe gynecological endocrinopathy that has a prolonged adverse consequence for women's physical and mental health is polycystic ovarian syndrome.

Even though the exact cause of PCOS is still unresolved family history research shows that this hormonal disorder is more common in some families than in the general population. Families with a history of PCOS in first-degree relatives are included in this hereditary factor. According to a study, 40% of the sisters of 93 PCOS patients and 35% of premenopausal women had the illness. According to another research study, out of 80 women with PCOS, 22% had sisters with the condition, and 24% had hyperandrogenism and regular periods. In 2012, the WHO estimated that 116 million women worldwide (3.4%) were living with PCOS. This condition, with an uncertain etiology and heterogeneous presentation, affects 5–10% of women during their reproductive years. Prevalence rates differ widely on a global scale, ranging between 2.2% and 26%. Pakistani women have a higher prevalence of PCOS (52%), compared to Western Caucasian women (20-25% in the UK).

Due to the high financial expenditures and numerous adverse reactions of using allopathic medications, there has recently been an increased demand for herbal remedies. Herbal plants have been a significant source of therapeutic strategies since ancient times. Remarkably, despite the significant advancements in pharmaceuticals, the use of herbal remedies is growing daily in emerging nations.

Thousands of medicinal plants that have a powerful effect on PCOS symptoms are still used worldwide, despite the early 20th century revolution in pharmaceutical chemistry that made it easier to synthesize a vast array of medicinal drug molecules and enabled the treatment of diseases that were previously incurable [9]. Environmental and genetic factors combine to cause PCOS. Having a family history of the illness, being obese, and not exercising are risk factors. Two of the three findings listed below serve as the basis for the diagnosis: Ovarian cysts, increased testosterone levels, and no ovulation. Ultrasound may be able to identify cysts. Similar symptoms can also be produced by hypothyroidism, adrenal hyperplasia, and elevated prolactin levels in the blood.

The pathophysiology of several distinct illnesses strongly connects PCOS, which can be generally characterized into metabolic dysfunction, biochemical dysfunction, reproductive dysfunction, and endocrine dysfunction. Moreover, psychological impairments including sadness and other mood disorders are linked to it. A large proportion of women with PCOS are affected by overweight or obesity. These weight-related factors contribute to increased androgen production, impaired metabolic regulation, and reproductive dysfunction. PCOS may coexist with metabolic disorders like dyslipidemia, insulin resistance, and therefore, conditions like diabetes, obesity, cancer, infertility, and coronary heart disease.

1. PATHOPHYSIOLOGY

The disturbed physiological process linked to the disease, known as pathophysiology, includes the functional alterations brought on by the illness or injury. The pathophysiology of PCOS is complex and involves several interrelated factors. These include impaired insulin sensitivity, abdominal adiposity, androgen excess, and dysfunction of the hypothalamic-pituitary-ovarian axis due to altered steroidogenesis. Each of these flaws contributes to the development of PCOS. By losing weight we might overcome this disorder because it is often observed that fat deposition or an elevated BMI speeds up insulin resistance and hyperandrogenism. Expansion of adipose tissue stimulates ovarian theca cells to increase androgen production, leading to Elevated androgen levels.

In PCOS Individuals, the pituitary gland secretes more LH due to biochemical disruption that disrupts the menstrual cycle.The lack of mature follicles will lead to infertility. Some follicles might not disintegrate; instead, they might remain in vivo and mature into formations known as cysts, which are fluid-filled sacs. Increased testosterone production from elevated insulin and LH levels results in hirsutism, acne, and the inhibition of ovulation, all of which worsen infertility. In PCOS, excessive androgen activity is thought to be a pivotal factor in the progression of endocrine and metabolic dysfunctions. A glycoprotein called sex hormone-binding globulin (SHBG) controls the bioavailability of sex steroid hormones, and there is a correlation between SHBG levels and PCOS risk. Insulin resistance, hyperandrogenism, diabetes type 2, glucose intolerance, obesity, infertility, and cardiovascular disease (CVD) were all more common in Females affected by PCOS with low SHBG levels. Because PCOS has a complicated and multifactorial etiology influenced by a variety of genetic and environmental variables, its pathophysiology is not well established. Generally speaking, hyperandrogenism and hyperinsulinemia play key roles in PCOS pathogenesis. By stimulating one another, these two factors result in a number of metabolic abnormalities, including as obesity, insulin resistance, dyslipidemia, type 2 diabetes, elevated inflammation, and oxidative stress.

Causes of PCOS

A few significant causes of PCOS are as follows:

- Genetic susceptibility
- Adrenal hyperactivity in childhood
- Elevated insulin levels
- An imbalance in hormones
- Stress

Factors such as hypothalamic-pituitary dysfunction, ovarian dysfunction, and elevated insulin levels are believed to play significant roles in the development of PCOS, although the exact causes remain complex and not fully understood.

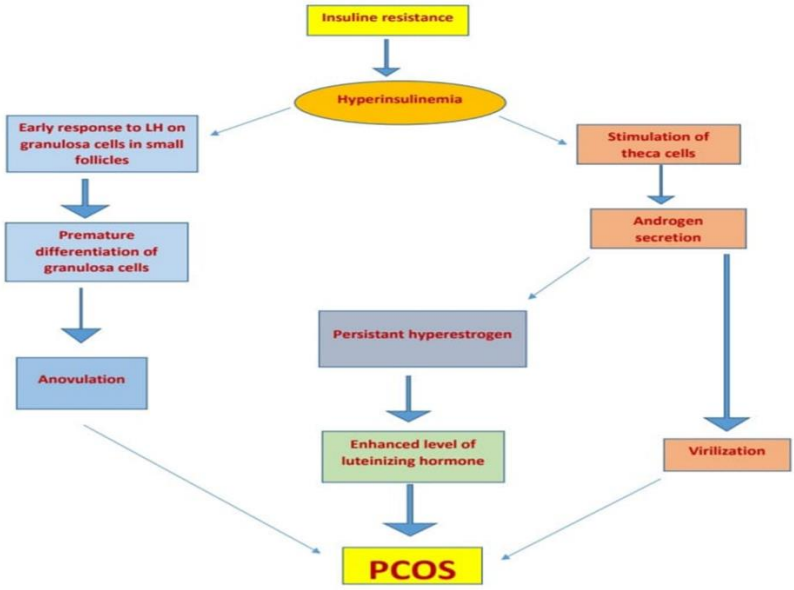


Figure 1. |Pathophysiological Mechanisms Linking Insulin Resistance to PCOS.

2. GENETIC SUSCEPTIBILITY

PCOS is a highly heterogeneous and intricate condition. The genetic foundations of PCOS differ across families and even within the same family, though they typically converge on a shared pathogenic pathway. Due to the complexity and variability of the disorder, no single gene or specific set of genes has been consistently linked to its development within families. Additionally, the genetic susceptibility to PCOS may vary among individuals within the same family. Intrauterine programming has recently been proposed as a potential risk factor for PCOS. It is impractical to use genome screening to look for a potential gene in a complex condition like PCOS. In these kinds of families, linkage analysis invariably yields negative results. Genome-wide association studies (GWAS) and case-control studies with a larger population size are useful in identifying potential associations in such a condition. Although it is frequently impractical to analyze parents in cases of such diseases, the known risk of disease can be estimated.

Adrenal Hyperactivity In Childhood

A defect in a key adrenal enzyme of the steroidogenesis pathway underlies congenital adrenal hyperplasia (CAH), which is inherited in an autosomal recessive manner. Reduced levels of cortisol and aldosterone, as well as an excess of adrenal androgens, are the results of CAH. PCOS development in CAH patients is influenced by aberrant adrenal steroidogenesis. Cortisol production is decreased in these people. Adrenocorticotropic hormone (ACTH) secretion rises as a result, stimulating the adrenal glands and increasing androgen secretion. The virilizing effects of increased androgen production can cause hirsutism, male-pattern baldness, and irregular menstruation in affected girls PCOS, which alters enzyme activity and results in cortisol shortage, is a risk factor for female patients with CAH. Consequently, while excess cortisol precursor buildup raises androgen production, rising ACTH levels activate the adrenal cortex.

Elevated Insulin Levels

The improper response to insulin in metabolically active marginal tissues, such as skeletal muscle and adipose tissue, is the cause of inherent insulin resistance in PCOS. The coexistence of obesity and PCOS frequently predisposes women to insulin resistance, contributing to dysregulated glucose and lipid metabolism. Additionally, raising insulin inhibits follicle production, resulting in irregular menses and impotence, by lowering the quantity of sex hormone-binding globulin (SHBG) in the blood and encouraging free androgens. The consumption of a diet high in sugar (white bread and fried potatoes) was considerably higher among PCOS females.

Overproduction of insulin can worsen the ovary's and glands' excretion of androgen by activating the pituitary gland's insulin receptors to release luteinizing hormone. It increases levels of free testosterone and may limit the production of hepatic SHBG. Excessive androgen excretion might hinder the growth of ovarian follicles and cause symptoms of alopecia and acne. Insulin, in particular, is a vital hormone in females of reproductive age, as demonstrated by the link between PCOS and insulin resistance. Additionally, ovulation requires central nervous system insulin action.

Insulin resistance has been linked to either delayed or reduced egg production, according to research. Additionally, androgens significantly affect insulin secretion and sensitivity.

Hormonal Imbalance

Functional ovarian hyperandrogenism (FOH) is the cause of all PCOS. In PCOS, functional ovarian hyperandrogenism—seen in nearly 66% of presentations—arises from disrupted androgen synthesis and a pronounced 17-OHP response to gonadotropin stimulation. When adrenal androgen synthesis is suppressed, testosterone increase is observed in the residual PCOS, despite the abnormal FOH response of 17-OHP. Isolated functional adrenal hyperandrogenism is associated with PCOS in approximately 3% of patients. The pulsatile gonadotropin-releasing hormone release is
altered by ovarian hormonal dysregulation, which may result in a relative increase in the production and secretion of LH as opposed to follicle-stimulating hormone (FSH).

Stress

The role of stress in the development of PCOS has gained increasing attention in recent years. Nevertheless, its impact on psychological well-being is often overlooked, despite the clear clinical presentation of anovulation, hirsutism, and polycystic ovaries. Undoubtedly, a number of authors have stated that women with PCOS are more prone to experience stress than women in their age group who are in good health. They are recognized to be psychologically morbid and to display symptoms like despair and anxiety. According to studies, women with PCOS are more likely to experience anxiety, depression, mood swings, obsessive-compulsive behaviors, eating disorders, and a lower quality of life. Additionally, research has shown that anovulation brought on by stress might result in infertility. This highlights the need to address both the physical and emotional aspects of the condition. Psychological support and stress-management strategies can play a meaningful role in improving overall well-being. Studies further indicate that reducing stress may help regulate hormonal balance and improve reproductive outcomes.

Herbal Remedies for Managing PCOS

The therapeutic benefits and applications of herbs are well-documented. As modern society increasingly relies on synthetic drugs, their associated side effects and complications have led to a renewed interest in natural and plant-based medicines. Scientific research has confirmed the efficacy and safety of various complementary medicine approaches, including herbal treatments, for managing certain diseases.

Cinnamomum verum

Cinnamon has been traditionally used across different cultures for centuries due to its medicinal properties. In addition to its well-known benefits like reducing blood glucose and serum lipid levels, it has also been found helpful in regulating menstrual cycles and treating gynecological, respiratory, and digestive issues. Research from both laboratory and animal studies suggests that cinnamon may help reduce insulin resistance (IR) by enhancing insulin function, activating insulin signaling pathways, and improving insulin sensitivity. This process plays a crucial role in boosting insulin-stimulated glucose uptake and promoting glycogen production. Several studies have confirmed cinnamon's potential to lower glucose levels, supporting its use in managing IR. Given the role of IR in the development of PCOS, cinnamon may offer an alternative treatment for this condition.

A clinical study found that taking cinnamon daily for 3 months led to a decrease in fasting serum insulin (FSI) levels and improved IR in women with PCOS. In line with these findings, another study reported a significant reduction in IR after 8 weeks of oral cinnamon extract. However, contrary to these studies, one study found that consuming cinnamon daily for 6 months did not reduce IR in women with PCOS.

Aloe arborescens

Aloe vera, also referred to as Aloe arborescens, is a perennial herbaceous plant belonging to the Liliaceae family. It is rich in vitamins A, C, and E and exhibits antioxidant properties by lowering lipid peroxidation levels. Additionally, Aloe vera contains essential nutrients, minerals, salicylic acid, enzymes, tannins, and various polysaccharides.

It has been demonstrated that aloe vera improves ovarian tissue and folliculogenesis and increases the number of germ cells in the ovary. The polysaccharide compounds in Aloe vera gel possess anti-inflammatory properties, aiding in the reduction and repair of inflammation. Additionally, these compounds exhibit antibacterial and antimicrobial effects.

A study investigated the effects of Aloe vera gel on PCOS-induced rats. Female rats were administered letrozole orally for five months without the use of nonsteroidal aromatase inhibitors to induce PCOS. They were then treated with 1 ml of Aloe vera gel for 45 days. Researchers assessed the stress cycle, glucose sensitivity, and steroidogenic activity in the rats. Findings revealed that the combination of letrozole and Aloe vera gel helped prevent PCOS development. Aloe vera gel exhibited a protective effect by restoring ovarian steroid balance and modifying steroidogenic activity, which is attributed to its plant compounds, such as phytosterols and phytophenols. Additionally, Aloe vera gel directly influences key enzymes like 3β-HSD by reducing enzyme activity and regulating estradiol formation.

Mentha spicata

In many nations, tea, which is made from the fresh leaves of Mentha spicata, is a popular beverage that is drunk every day. These days, a lot of people are curious in how effective it is at preventing different illnesses. Tea has several health benefits, including boosting immunity, managing glucose and lipid metabolic disorders, and activating the central nervous system. It also contains more than 20 components that the human body needs.Furthermore, it has been demonstrated that tea and tea extracts improve body weight, insulin, glucose, body fat rate (BFR), and free testosterone (FT) in PCOS patients. According to the analysis, women with PCOS who use tea supplements may have a considerable drop in their body weight and FBG and FINS levels. In addition to the aforementioned benefits, green tea significantly improves a number of reproductive hormone indices. Additionally, using tea supplements is a somewhat safe treatment for those with PCOS.

Linum usitassimum

A member of the Linaceae family, flax (Linum usitatissimum) is an annual herb with blue blossoms that bears flat seeds of varying colors, typically golden yellow to deep reddish brown.Flaxseed has a nutty flavor and a crunchy texture.

Flaxseed is regarded as a functional food since it is rich in dietary fiber, phytoestrogenic lignans, and α-linolenic acid (ALA). ALA is an important fatty acid that can be transformed into other n-3 LCFAs, including docosahexaenoic acid (DHA) and eicosapentaenoic acid.Additionally, it was found that taking flaxseed supplements reduced hirsutism and plasma testosterone levels in a PCOS patient in a clinically significant way.

According to an experimental study of pcos in a rat model,by lowering the expression of the genes for steroidogenic acute regulator (StAR) and CYP11A1 (a protein of the cytochrome P450 family involved in the metabolism of androgens in PCOS pathogenesis), flaxseed oil consumption is implicated in preventing the conversion of cholesterol to testosterone.

Foeniculum vulgare

The well-known Mediterranean fragrant plant fennel (Foeniculum vulgare) is used as a spice and in traditional medicine. Fennel fruit has also been shown to have antioxidant, diuretic, analgesic, and antipyretic properties [Because of its strong antioxidant properties, it protects cells against oxidative damage. The compound anethole promotes menstruation and makes delivery easier. LH and testosterone levels are negatively impacted by prolonged use of Foeniculum vulgare. In women with PCOS, lowering androgen levels might result in a decrease in LH, which can Lead to a normal menstrual cycle. The extract from Foeniculum vulgare lowers urea but has no effect on creatinine levels. According to scientific research, rats given a small amount of Foeniculum vulgare had lower progesterone levels than the control group. According to a different study, PCOS patients' days between menstrual cycles and dysmenorrhea pain were reduced with Foeniculum vulgare.

Chamomilla matricaria

Chamomile (Chamomilla matricaria), a perennial species of the Asteraceae family, contains several bioactive constituents, including gallic acid, chamazulene, farnesene, matricin, coumarin derivatives, apigenin, and choline. These flavonoids and antioxidant compounds collectively contribute in its anti-inflammatory properties. Chamomile's antispasmodic properties lessen women's risk of preterm labor and menstrual cramps.

Because chamomile stimulates leukocytes (macrophages and B lymphocytes), it is used to treat eczema and other skin conditions. Dried Matricaria chamomilla flower extract not only helps rats recover from a PCO condition that was generated, which is likely caused by the GABA system working in tandem with chamomile's effects on controlling LH surge release, but it also promotes the growth of dominant follicles. It results in improved endometrial tissue configurations in the uterus. By reducing testosterone, preventing apoptosis, and acting as an antioxidant, chamomile extract helps repair kidney damage linked to PCOS. With Met treatment, serum levels of BUN and urea may rise.

Vitex agnus-castus

Vitex agnus castus, commonly referred to as chaste berry, belongs to the Verbenaceae family and has been utilized in herbal medicine for approximately 2000 years. This large shrub is indigenous to Europe and is also widely found in southern parts of the United States. An imbalance in estrogen levels can lead to menstrual cycle irregularities and premenstrual syndrome, which includes issues like corpus luteum deficiency, cyclical mastalgia, and hot flashes after menopause. The extract of Vitex agnus-castus includes ligands for dopamine, opioid, and estrogen receptors, which influence hormone levels and reduce prolactin levels. The extract of Vitex agnus-castus includes ligands for dopamine, opioid, and estrogen receptors, which influence hormone levels and reduce prolactin levels . The administration of Vitagnus extract to PCOS-afflicted animals resulted in a substantial normalization of the LH/FSH ratio, a significant decrease in testosterone levels, and a notable increase in estrogen levels.

Additionally, treatment with this herb resulted in fewer follicular cysts, an increased number of antral and Graafian follicles, and a reduction in the thickness of the theca layer in the PCOS animals. These findings indicate that Vitagnus extract alleviated the symptoms related to ovarian syndrome and facilitated the restoration of ovulation in the ovaries.

Cocos nucifera

Cocos nucifera is part of the Arecaceae family. The oil is mainly composed of alpha-tocopherol and lauric acid, while the roots are abundant in phenolic compounds like flavonoids and saponins.

This herb aso influences the concentrations of sex hormones in the blood, including FSH and LH. Preclinical studies have demonstrated that Cocos nucifera positively influences ovarian histology in patients with PCOS, specifically regarding the size and quantity of cysts. In addition, it reduces ovarian weight while promoting an increase in uterine weight. Through hormonal regulation, it may help in preventing the formation of ovarian cysts. In India, oral infusions made from coconut inflorescence are utilized to address disorders related to the menstrual cycle.

Curcuma longa

A naturally occurring polyphenol called curcumin (diferuloylmethane) is taken from the roots of Curcuma longa (Zingiberaceae). A number of chronic illnesses, including diabetes, depression, and others, are treated with it due to its anti-inflammatory, hypolipidemic, and anti-anxiety properties. It is clear that curcumin protects ovarian tissue. Indeed, it appears that this substance contributes to the suppression of ovarian angiogenesis, ovarian fibrosis prevention, and matrix degradation by suppressing the expression of vascular endothelial growth factor (VEGF), a proangiogenic factor intimately linked to the development of PCOS. According to a scientific research curcumin's anti-inflammatory and antioxidant properties for PCOS may be due to its inhibitory effects on the levels of serum interleukin-6 (IL-6), tumor necrosis factor-alpha (TNF-α), and C-reactive protein (CRP) expression.

According to a different study, women with PCOS who received curcumin therapy for 12 weeks saw improvements in their body weight, glycemic control, blood lipid levels (apart from triglycerides and VLDL cholesterol), and the expression of the genes for the low-density lipoprotein receptor (LDLR) and peroxisome proliferated-activator receptor gamma (PPAR-γ).

Stachys lavandulifolia

The Lamiaceae family includes Stachys, which is known by its scientific name, Stachys lavandulifolia. Traditionally, the herb has been employed for its rheumatic analgesic effects, its ability to induce menstruation, and as an abortifacient, as well as for easing primary dysmenorrhea discomfort. Phytochemical analyses demonstrate that it contains flavonoids, ethanolides, terpenoids, saponins, quinones, iridoids, phenolic acids, and diterpenoids.

66 PCOS patients were split into two groups at random in a 2013 study. For three months, the patients in the intervention group (n=33) received five grams of tea brewed from Stachys lavandulifolia three times a day. For three months, the patients in the control group were given 10 mg of medroxyprogesterone acetate (MPA) every night for ten nights a month. Observed levels of abnormal uterine bleeding (AUB) in the two groups did not differ significantly. In contrast to the control group, the intervention group experienced less adverse effects. This difference was not substantial, though. Consequently, it was determined that Stachys lavandulifolia might be utilized in place of MPA to treat PCOS-induced AUB.

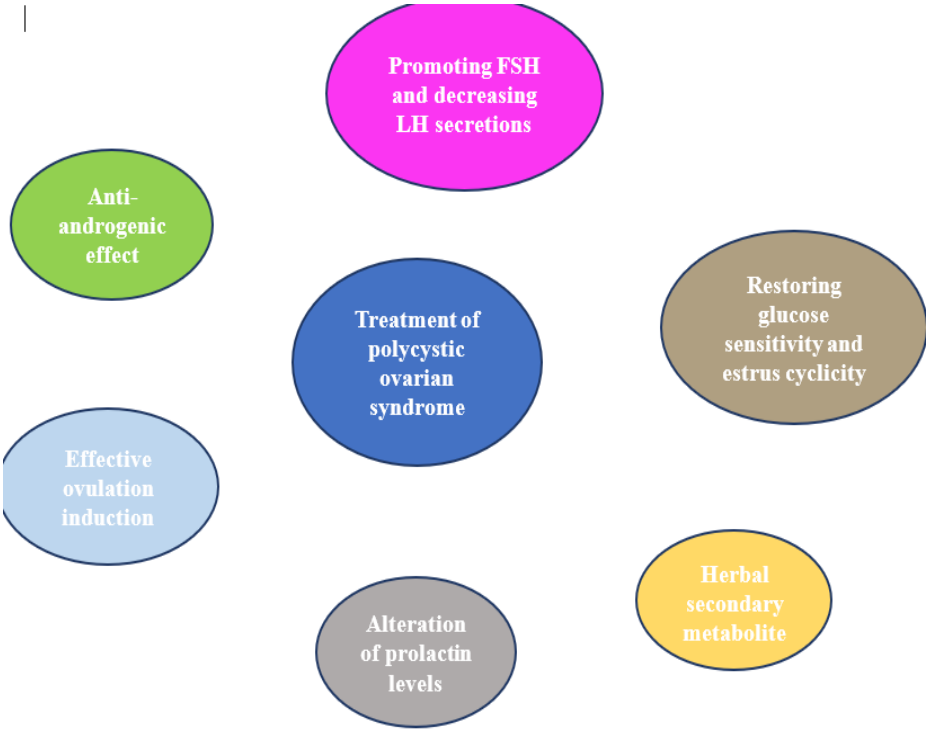


Figure 2. Treatment of polycystic ovarian syndrome

CONCLUSION

Polycystic ovarian syndrome continues to be a complex hormonal disorder or pathophysiological condition of metabolic, endocrine, and reproductive dysfunction. Although the underlying cause of PCOS is not completely understood, the consequences of the disease on women's health, especially with respect to infertility, metabolic disorders, and psychological well-being, are significant. The rising need toward alternative treatments, especially herbal products, is motivated by side effects and costs of the pharmaceutical agents. Various herbal remedies like cinnamon, aloe vera, spearmint, and flaxseed have proved to be highly effective herbs for relieving symptoms of PCOS through the modulation of the main pathophysiological mechanisms like insulin resistance, hormonal changes, and inflammation.

Herbal remedies also represent promising adjunctive therapies that could potentially complement conventional treatments, enhancing clinical outcomes while minimizing the adverse effects. To summarize, although more investigation is needed to form proper clinical recommendations, the role of herbal medicine in PCOS treatment shows great promise for women who want a more holistic and less invasive therapeutic approach in addressing their condition. Tailoring treatment to the individual, and integrating both old and new medicines, could improve the way this ubiquitous disorder is handled.

Table 1. Medicinal Plants and Their Therapeutic Benefits in PCOS Management

Sr.No	Name	Scientific Name	Family	Part Used	Benefits
1	Bitter melon	*Memordica charantia*	Cucurbitaceae	Fruit	Antioxidant effect
2	Black seed	*Nigella sativa*	Ranunculaceae	seed	Anti oxidative,anti inflammatory
3	Pomegranate	*Punica granatum*	Punicaceae	Seeds,flowers	Anti inflammatory
4	Rose	*Rosa damascena*	Rosaceae	Petals	Anti inflammatory
5	Sesame	*Sesamum indicum*	Pedaliaceae	seed	Anti mutagenic
6	Ashwagandha	*Withania somnifera*	Solanaceae	Root	Anti stress
7	Lodhra	*Symplocos racemosa*	symplocacea	Bark	Anti androgenic
8	Liquorice	*Glycyrrhiza glabra*	Fabaceae	Root	Anti androgenic
9	Black cohosh	*Actaea racemosa*	Ranunculaceae	Root and rhizome	Anti oxidative
10	White peony	*Paeonia lactiflora*	Paeoniaceae	leaves	Anti androgenic
11	Nettle	*Urtica dioica*	urticaceae	Root,leaves	Hypolipidemic effect
12	Sarphoka	*Tephrosia purpurea*	Fabaceae	Roots	Fertility enhancing effect

REFERENCES

Akbar, S. (2020). Aloe vera (L.) Burm.f. (Asphodelaceae/Xanthorrhoeaceae). In Handbook of 200 medicinal plants (pp. 187–206). Springer. https://doi.org/10.1007/978-3-030-16807-0

Ashkar, F., Rezaei, S., Salahshoornezhad, S., Vahid, F., Gholamalizadeh, M., Dahka, S. M., & Doaei, S. (2020). The Role of medicinal herbs in treatment of insulin resistance in patients with Polycystic Ovary Syndrome: A literature review. Biomolecular concepts, 11(1), 57–75. https://doi.org/10.1515/bmc-2020-0005

Barrea, L., Arnone, A., Annunziata, G., Muscogiuri, G., Laudisio, D., Salzano, Carvalho, L. M. L., Dos Reis, F. M., Candido, A. L., Nunes, F. F. C., Ferreira, C. N., & Gomes, K. B. (2018). Polycystic Ovary Syndrome as a systemic disease with multiple molecular pathways: a narrative review. Endocrine regulations, 52(4), 208–221. https://doi.org/10.2478/enr-2018-0026

Basu, B. R., Chowdhury, O., & Saha, S. K. (2018). Possible Link Between Stress-related Factors and Altered Body Composition in Women with Polycystic Ovarian Syndrome. Journal of human reproductive sciences, 11(1), 10–18. https://doi.org/10.4103/jhrs.JHRS_78_17

Bhandary, M. J., Chandrashekar, K. R., & Kaveriappa, K. M. (1995). Medical ethnobotany of the Siddis of Uttara Kannada district, Karnataka, India. Journal of ethnopharmacology, 47(3), 149–158.

Bigomi, M., Javadian, E., Bigomi, Z., Rouhani, R., & Ghanaei, S. (2024). A review of medicinal plants in the therapy of polycystic ovary syndrome (PCOS) in women. Gene, Cell and Tissue, 11(4), e142604. https://doi.org/10.5812/gct-142604

Chen, S. N., Friesen, J. B., Webster, D., Nikolic, D., van Breemen, R. B., Wang, Z. J., Fong, H. H., Farnsworth, N. R., & Pauli, G. F. (2011). Phytoconstituents from Vitex agnus-castus fruits. Fitoterapia, 82(4), 528–533. https://doi.org/10.1016/j.fitote.2010.12.003

Cherbal, A., Bouabdallah, M., Benhalla, M., Hireche, S., & Desdous, R. (2023). Phytochemical Screening, Phenolic Content, and Anti-Inflammatory Effect of Foeniculum vulgare Seed Extract. Preventive nutrition and food science, 28(2), 141–148. https://doi.org/10.3746/pnf.2023.28.2.141

Choudhary, K., Singh, R., Garg, A., Verma, N., Purohit, A., & Deora, D. (2019). An updated overview of polycystic ovary syndrome. International Journal of Biological Sciences, 7(3), 1–13.

Cooney, L. G., Lee, I., Sammel, M. D., & Dokras, A. (2017). High prevalence of moderate and severe depressive and anxiety symptoms in polycystic ovary syndrome: a systematic review and meta-analysis. Human reproduction (Oxford, England), 32(5), 1075–1091. https://doi.org/10.1093/humrep/dex044

Costa, C. T., Bevilaqua, C. M., Morais, S. M., Camurça-Vasconcelos, A. L., Maciel, M. V., Braga, R. R., & Oliveira, L. M. (2010). Anthelmintic activity of Cocos nucifera L. on intestinal nematodes of mice. Research in veterinary science, 88(1), 101–103.

Escobar-Morreale H. F. (2018). Polycystic ovary syndrome: definition, aetiology, diagnosis and treatment. Nature reviews. Endocrinology, 14(5), 270–284. https://doi.org/10.1038/nrendo.2018.24

Farhoudi, L., Kesharwani, P., Majeed, M., Johnston, T. P., & Sahebkar, A. (2022). Polymeric nanomicelles of curcumin: Potential applications in cancer. International journal of pharmaceutics, 617, 121622. https://doi.org/10.1016/j.ijpharm.2022.121622

Farideh, Z. Z., Bagher, M., Ashraf, A., Akram, A., & Kazem, M. (2010). Effects of chamomile extract on biochemical and clinical parameters in a rat model of polycystic ovary syndrome. Journal of reproduction & infertility, 11(3), 169–174.

Feyzollahi, Z., Mohseni Kouchesfehani, H., Jalali, H., Eslimi-Esfahani, D., & Sheikh Hosseini, A. (2021). Effect of Vitex agnus-castus ethanolic extract on hypothalamic KISS-1 gene expression in a rat model of polycystic ovary syndrome. Avicenna journal of phytomedicine, 11(3), 292–301.

Flück, C. E., & Miller, W. L. (2006). P450 oxidoreductase deficiency: a new form of congenital adrenal hyperplasia. Current opinion in pediatrics, 18(4), 435–441. https://doi.org/10.1097/01.mop.0000236395.71956.5c

Fu, Q. Y., Li, Q. S., Lin, X. M., Qiao, R. Y., Yang, R., Li, X. M., Dong, Z. B., Xiang, L. P., Zheng, X. Q., Lu, J. L., Yuan, C. B., Ye, J. H., & Liang, Y.

R. (2017). Antidiabetic Effects of Tea. Molecules (Basel, Switzerland), 22(5), 849. https://doi.org/10.3390/molecules22050849

Goodarzi, M. O., Dumesic, D. A., Chazenbalk, G., & Azziz, R. (2011). Polycystic ovary syndrome: etiology, pathogenesis and diagnosis. Nature reviews. Endocrinology, 7(4), 219–231.

Hamsarekha, P., Suvarchala, S., Yashaswini, P., Nousheen, S., & Mitta, S. G. (2023, November). Polycystic ovary syndrome: A review. International Journal of Emerging Technologies and Innovative Research, 10(11), f307–f315. http://www.jetir.org/papers/JETIR2311534.pdf

He, F. F., & Li, Y. M. (2020). Role of gut microbiota in the development of insulin resistance and the mechanism underlying polycystic ovary syndrome: a review. Journal of ovarian research, 13(1), 73. https://doi.org/10.1186/s13048-020-00670-3

Heshmati, J., Sepidarkish, M., Morvaridzadeh, M., Farsi, F., Tripathi, N., Razavi, M., & Rezaeinejad, M. (2021). The effect of cinnamon supplementation on glycemic control in women with polycystic ovary syndrome: A systematic review and meta-analysis. Journal of food biochemistry, 45(1), e13543. https://doi.org/10.1111/jfbc.13543

Heskes, A. M., Sundram, T. C. M., Boughton, B. A., Jensen, N. B., Hansen, N. L., Crocoll, C., Cozzi, F., Rasmussen, S., Hamberger, B., Hamberger, B., Staerk, D., Møller, B. L., & Pateraki, I. (2018). Biosynthesis of bioactive diterpenoids in the medicinal plant Vitex agnus-castus. The Plant journal : for cell and molecular biology, 93(5), 943–958.

Hininger-Favier, I., Benaraba, R., Coves, S., Anderson, R. A., & Roussel, A. M. (2009). Green tea extract decreases oxidative stress and improves insulin sensitivity in an animal model of insulin resistance, the fructose-fed rat. Journal of the American College of Nutrition, 28(4), 355–361. https://doi.org/10.1080/07315724.2009.10718097

Jalilian, N., Modarresi, M., Rezaie, M., Ghaderi, L., & Bozorgmanesh, M. (2013). Phytotherapeutic management of polycystic ovary syndrome: role of aerial parts of wood betony (Stachys lavandulifolia). Phytotherapy research : PTR, 27(11), 1708–1713.

Jamilian, M., Foroozanfard, F., Kavossian, E., Aghadavod, E., Shafabakhsh, R., Hoseini, A., & Asemi, Z. (2020). Effects of curcumin on body weight,

glycemic control and serum lipids in women with polycystic ovary syndrome: A randomized, double-blind, placebo-controlled trial. Clinical nutrition ESPEN, 36, 128–133.

Joham, A. E., Norman, R. J., Stener-Victorin, E., Legro, R. S., Franks, S., Moran, L. J., Boyle, J., & Teede, H. J. (2022). Polycystic ovary syndrome. The lancet. Diabetes & endocrinology, 10(9), 668–680.

Kantivan, P. G., Khale, A. R., & Ogale, S. (2012). Natural remedies for polycystic ovarian syndrome (PCOS): A review. International Journal of Pharmacology and Phytopharmacological Research

Kajla, P., Sharma, A., & Sood, D. R. (2015). Flaxseed-a potential functional food source. Journal of food science and technology, 52(4), 1857–1871. https://doi.org/10.1007/s13197-014-1293-y

Khafagy, G., El Sayed, I., Abbas, S., & Soliman, S. (2020). Perceived Stress Scale Among Adolescents with Polycystic Ovary Syndrome. International journal of women's health, 12, 1253–1258. https://doi.org/10.2147/IJWH.S279245

Kolivand, M. , Keramat, A. and Khosravi, A. (2017). The Effect of Herbal Teas on Management of Polycystic Ovary Syndrome: A Systematic Review. Journal of Midwifery and Reproductive Health, 5(4), 1098-1106. doi: 10.22038/jmrh.2017.9368

Lamanna-Rama, N., Romero-Miguel, D., Desco, M., & Soto-Montenegro, M. L. (2022). An Update on the Exploratory Use of Curcumin in Neuropsychiatric Disorders. Antioxidants (Basel, Switzerland), 11(2), 353. https://doi.org/10.3390/antiox11020353

Liu, J., Burdette, J. E., Xu, H., Gu, C., van Breemen, R. B., Bhat, K. P., Booth, N., Constantinou, A. I., Pezzuto, J. M., Fong, H. H., Farnsworth, N. R., & Bolton, J. L. (2001). Evaluation of estrogenic activity of plant extracts for the potential treatment of menopausal symptoms. Journal of agricultural and food chemistry, 49(5), 2472–2479. https://doi.org/10.1021/jf0014157

Lima, E. B., Sousa, C. N., Meneses, L. N., Ximenes, N. C., Santos Júnior, M. A., Vasconcelos, G. S., Lima, N. B., Patrocínio, M. C., Macedo, D., & Vasconcelos, S. M. (2015). Cocos nucifera (L.) (Arecaceae): A phytochemical and pharmacological review. Brazilian journal of medical

and biological research = Revista brasileira de pesquisas medicas e biologica, 48(11), 953–964.

Livadas, S., Dracopoulou, M., Dastamani, A., Sertedaki, A., Maniati-Christidi, M., Magiakou, A. M., Kanaka-Gantenbein, C., Chrousos, G. P., & Dacou-Voutetakis, C. (2015). The spectrum of clinical, hormonal and molecular findings in 280 individuals with nonclassical congenital adrenal hyperplasia caused by mutations of the CYP21A2 gene. Clinical endocrinology, 82(4), 543–549. https://doi.org/10.1111/cen.12543

Maleki, V., Faghfouri, A. H., Tabrizi, F. P. F., Moludi, J., Saleh-Ghadimi, S., Jafari-Vayghan, H., & Qaisar, S. A. (2021). Mechanistic and therapeutic insight into the effects of cinnamon in polycystic ovary syndrome: a systematic review. Journal of ovarian research, 14(1), 130. https://doi.org/10.1186/s13048-021-00870-5

Marciniak, A., Lejman-Larysz, K., Nawrocka-Rutkowska, J., Brodowska, A., & Songin, D. (2018). Zespół policystycznych jajników – aktualny stan wiedzy [Polycystic ovary syndrome - current state of knowledge]. Polski merkuriusz lekarski : organ Polskiego Towarzystwa Lekarskiego, 44(264), 296–301.

Maharjan, R., Nagar, P. S., & Nampoothiri, L. (2010). Effect of Aloe barbadensis Mill. formulation on Letrozole induced polycystic ovarian syndrome rat model. Journal of Ayurveda and integrative medicine, 1(4), 273–279. https://doi.org/10.4103/0975-9476.74090

McKay, D. L., & Blumberg, J. B. (2006). A review of the bioactivity and potential health benefits of peppermint tea (Mentha piperita L.). Phytotherapy research : PTR, 20(8), 619–633.

Mehreen, T. S., Ranjani, H., Kamalesh, R., Ram, U., Anjana, R. M., & Mohan, V. (2022). Prevalence of polycystic ovarian syndrome among adolescents and young women in India. Journal of Diabetology, 12(3), 319. https://doi.org/10.4103/JOD.JOD_105_20

Merz, P. G., Gorkow, C., Schrödter, A., Rietbrock, S., Sieder, C., Loew, D., Dericks-Tan, J. S., & Taubert, H. D. (1996). The effects of a special Agnus castus extract (BP1095E1) on prolactin secretion in healthy male subjects. Experimental and clinical endocrinology & diabetes : official

journal, German Society of Endocrinology [and] German Diabetes Association, 104(6), 447–453. https://doi.org/10.1055/s-0029-1211483

Mezzetti, M., Minuti, A., Bionaz, M., Piccioli-Cappelli, F., & Trevisi, E. (2020). Effects of Aloe arborescens Whole Plant Homogenate on Lipid Metabolism, Inflammatory Conditions and Liver Function of Dairy Cows during the Transition Period. Animals : an open access journal from MDPI, 10(5), 917. https://doi.org/10.3390/ani10050917

Mnif, M. F., Kamoun, M., Kacem, F. H., Mnif, F., Charfi, N., Naceur, B. B., Rekik, N., & Abid, M. (2013). Reproductive outcomes of female patients with congenital adrenal hyperplasia due to 21-hydroxylase defi ciency. Indian journal of endocrinology and metabolism, 17(5), 790–793. https://doi.org/10.4103/2230-8210.117196

Mohammadi, S., Karimzadeh Bardei, L., Hojati, V., Ghorbani, A. G., & Nabiuni, M. (2017). Anti-Inflammatory Effects of Curcumin on Insulin Resistance Index, Levels of Interleukin-6, C-Reactive Protein, and Liver Histology in Polycystic Ovary Syndrome-Induced Rats. Cell journal, 19(3), 425–433. https://doi.org/10.22074/cellj.2017.4415

Mokaberinejad, R., Rampisheh, Z., Aliasl, J., & Akhtari, E. (2019). The comparison of fennel infusion plus dry cupping versus metformin in management of oligomenorrhoea in patients with polycystic ovary syndrome: a randomised clinical trial. Journal of obstetrics and gynaecology : the journal of the Institute of Obstetrics and Gynaecology, 39(5), 652–658. https://doi.org/10.1080/01443615.2018.1541232

Nowak, D. A., Snyder, D. C., Brown, A. J., & Demark-Wahnefried, W. (2007). The Effect of Flaxseed Supplementation on Hormonal Levels Associated with Polycystic Ovarian Syndrome: A Case Study. Current topics in nutraceutical research, 5(4), 177–181.

Patibandla, S., Gallagher, J. J., Patibandla, L., Ansari, A. Z., Qazi, S., & Brown, S. F. (2024). Ayurvedic Herbal Medicines: A Literature Review of Their Applications in Female Reproductive Health. Cureus, 16(2), e55240. https://doi.org/10.7759/cureus.55240

Purwar, A., & Nagpure, S. (2022). Insulin Resistance in Polycystic Ovarian Syndrome. Cureus, 14(10), e30351.

Rubilar, M., Gutiérrez, C., Verdugo, M., Shene, C., & Sineiro, J. (2010). Flaxseed as a source of functional ingredients. Journal of Soil Science and Plant Nutrition, 10(3), 373–377. https://doi.org/10.4067/S0718-95162010000100011

Sadrefozalayi, S., & Farokhi, F. (2014). Effect of the aqueous extract of Foeniculum vulgare (fennel) on the kidney in experimental PCOS female rats. Avicenna journal of phytomedicine, 4(2), 110–117.

Shahidi, F. and Hossain, A. (2018) Bioactives in Spices, and Spice Oleoresins: Phytochemicals and Their Beneficial Effects in Food Preservation and Health Promotion. Journal of Food Bioactives, 3, 8-75.

Shen, W., Pan, Y., Jin, B., Zhang, Z., You, T., Qu, Y., Han, M., Yuan, X., & Zhang, Y. (2021). Effects of Tea Consumption on Anthropometric Parameters, Metabolic Indexes and Hormone Levels of Women with Polycystic Ovarian Syndrome: A Systematic Review and Meta-Analysis of Randomized Controlled Trials. Frontiers in endocrinology, 12, 736867. https://doi.org/10.3389/fendo.2021.736867

Siddiqui, S., Mateen, S., Ahmad, R., & Moin, S. (2022). A brief insight into the etiology, genetics, and immunology of polycystic ovarian syndrome (PCOS). Journal of assisted reproduction and genetics, 39(11), 2439–2473. https://doi.org/10.1007/s10815-022-02625-7

Srivastava, J. K., Pandey, M., & Gupta, S. (2009). Chamomile, a novel and selective COX-2 inhibitor with anti-inflammatory activity. Life sciences, 85(19-20), 663–669. https://doi.org/10.1016/j.lfs.2009.09.007

Stepto, N. K., Hiam, D., Gibson-Helm, M., Cassar, S., Harrison, C. L., Hutchison, S. K., Joham, A. E., Canny, B. J., Moreno-Asso, A., Strauss, B. J., Hatzirodos, N., Rodgers, R. J., & Teede, H. J. (2020). Exercise and insulin resistance in PCOS: muscle insulin signalling and fibrosis. Endocrine connections, 9(4), 346–359. https://doi.org/10.1530/EC-19-0551

Sumińska, M., Bogusz-Górna, K., Wegner, D., & Fichna, M. (2020). Non-Classic Disorder of Adrenal Steroidogenesis and Clinical Dilemmas in 21-Hydroxylase Deficiency Combined with Backdoor Androgen Pathway. Mini-Review and Case Report. International journal of molecular sciences, 21(13), 4622. https://doi.org/10.3390/ijms21134622

Tehrani, H. G., Allahdadian, M., Zarre, F., Ranjbar, H., & Allahdadian, F. (2017). Effect of green tea on metabolic and hormonal aspect of polycystic ovarian syndrome in overweight and obese women suffering from polycystic ovarian syndrome: A clinical trial. Journal of education and health promotion, 6, 36. https://doi.org/10.4103/jehp.jehp_67_15

Wang, J. G., Anderson, R. A., Graham, G. M., 3rd, Chu, M. C., Sauer, M. V., Guarnaccia, M. M., & Lobo, R. A. (2007). The effect of cinnamon extract on insulin resistance parameters in polycystic ovary syndrome: a pilot study. Fertility and sterility, 88(1), 240–243.

Webster, D. E., Lu, J., Chen, S. N., Farnsworth, N. R., & Wang, Z. J. (2006). Activation of the mu-opiate receptor by Vitex agnus-castus methanol extracts: implication for its use in PMS. Journal of ethnopharmacology, 106(2), 216–221. https://doi.org/10.1016/j.jep.2005.12.025

Witchel, S. F., Oberfield, S. E., & Peña, A. S. (2019). Polycystic Ovary Syndrome: Pathophysiology, Presentation, and Treatment With Emphasis on Adolescent Girls. Journal of the Endocrine Society, 3(8), 1545–1573. https://doi.org/10.1210/js.2019-00078

Xing, C., Li, C., & He, B. (2020). Insulin Sensitizers for Improving the Endocrine and Metabolic Profile in Overweight Women With PCOS. The Journal of clinical endocrinology and metabolism, 105(9), 2950–2963. https://doi.org/10.1210/clinem/dgaa337

Yadav, K., Ghadge, P., Langeh, A., Kalbhare, S., Phadtare, P., & Bhoite, R. (2020). A Review on Herbal Medicinal Plant for Treatment of Polycystic Ovarian Syndrome (PCOS). Asian Journal of Pharmaceutical Research and Development, 8(4), 83–87. https://doi.org/10.22270/ajprd.v8i4.799

Zeng, L. H., Rana, S., Hussain, L., Asif, M., Mehmood, M. H., Imran, I., Younas, A., Mahdy, A., Al-Joufi, F. A., & Abed, S. N. (2022). Polycystic Ovary Syndrome: A Disorder of Reproductive Age, Its Pathogenesis, and a Discussion on the Emerging Role of Herbal Remedies. Frontiers in pharmacology, 13, 874914. https://doi.org/10.3389/fphar.2022.874914

CHAPTER 3
EMERGING HORIZONS OF NANOMEDICINE IN DRUG DISCOVERY AND DEVELOPMENT

[1]T.D.G. LIYANAGE
[2]Thushara Indika SAMPATH

[1]Sri Lanka Institute of Nanotechnology, Nanotechnology and Science Park, Mahenwatta, Pitipana, Homagama.Sri Lanka, thathsaraniL@slintec.lk
[2]1Sri Lanka Institute of Nanotechnology, Nanotechnology and Science Park, Mahenwatta, Pitipana, Homagama.Sri Lanka, Department of Natural products Sri Lanka Institute of Nanotechnology, Nanotechnology and Science Park, thusharaI@slintec.lk, ORCID ID: 0000-0002-9217-3835

INTRODUCTION

Nanotechnology has gradually expanded from its origins in physics, chemistry and materials science into the biomedical domain, where it enables the design of interventions at the molecular and atomic scale. Materials within the range of 1-100 nanometers exhibit unique physicochemical behaviors, including increased surface area to volume ratio, altered optical properties and enhanced reactivity, which are not typically observed in their bulk forms (Yun et al., 2025). These nanoscale features make it possible to design carriers and sensors that interact directly with biomolecules such as DNA, proteins and cell membranes. nanoparticles, nanofibers and engineered nanostructures are therefore increasingly used for therapeutic and diagnostic purposes, where their structural precision can be exploited for improved outcomes. Lipid based nanocarriers have been especially prominent within drug delivery due to their biocompatibility and versatility in encapsulating hydrophobic and hydrophilic drugs (Lunardi & Kwon, 2024; Yun et al., 2025). Polymeric nanoparticles and dendrimeric platforms also provide controlled release and protection of unstable molecules, while metallic nanoparticles such as gold and silver, offer additional photothermal or imaging functions (Alfutaimani et al., 2024; Waheed et al., 2024). In recent years, biomimetic nanomedicine has emerged as a frontier where synthetic nanomaterials are cloaked with cell-derived membranes and enabling them to evade immune detection and extend circulation times (Alimohammadvand et al., 2024; Ijaz et al., 2024). The convergence of these strategies illustrates how nanotechnology has matured from a conceptual framework into a transformative toolkit for modern medicine. The continuous integration of biology, engineering, and computational modeling further expands the possibilities for precise manipulation of biological systems at the nanoscale. Such advancements have enabled the development of highly targeted therapies with minimized off-target effects, particularly in oncology and infectious disease management. Moreover, biomimetic approaches offer new avenues for overcoming biological barriers, enhancing drug bioavailability, and reducing systemic toxicity.

1. BACKGROUND OF NANOTECHNOLOGY IN MEDICINE

1.1 Evolution of Drug Discovery and Limitations of Conventional Drugs

The path of drug discovery has historically progressed from empirical screening of natural products to rational design supported by advances in chemistry, pharmacology and high-throughput screening. Despite these achievements, conventional drugs often face challenges related to solubility, stability, bioavailability and off target effects. As example, many small molecules fail during preclinical or clinical stages due to their inability to achieve effective therapeutic concentrations without producing systemic toxicity (Wu et al., 2025). Furthermore, macromolecules such as proteins and nucleic acids are prone to enzymatic degradation and rapid clearance, which further restricts their therapeutic utility (Alimohammadvand et al., 2024). Oncology provides a clear example of these limitations. Conventional chemotherapeutics, though effective in killing cancer cells, also damage rapidly dividing healthy cells, resulting in severe side effects such as immunosuppression and gastrointestinal toxicity (Waheed et al., 2024). High systemic doses are often necessary to achieve local tumor concentrations, which compounds the toxicity problem. In neurological diseases, therapeutic delivery is limited by the blood brain barrier (BBB), which blocks more than 98% of small molecules and virtually all large biologics (Zhang et al., 2024). Biologics, such as monoclonal antibodies, though specific, also suffer from immunogenicity and instability during circulation (Vaisman-Mentesh et al., 2020). The culmination of these limitations is evident in the high attrition rate of drug development pipelines, which remain long, expensive and often inefficient. This context underscores the urgency of innovative approaches such as nanomedicine, that can provide solutions to longstanding pharmacological challenges.

1.2 Rationale for Nanomedicine in Modern Healthcare

Nanomedicine addresses many of the barriers associated with traditional therapeutics by employing nanoscale carriers that offer improved pharmacokinetics, targeted distribution and controlled release.

Encapsulation of drugs within nanocarriers not only shields them from premature degradation but also extends their half life in systemic circulation. Passive targeting is achieved through the enhanced permeability and retention effect, which facilitates the accumulation of nanoparticles in tumor and inflamed tissues due to leaky vasculature (Bertrand, 2013).

Active targeting further enhances specificity by attaching ligands, antibodies, or aptamers to nanocarrier surfaces and thereby directing them to receptors overexpressed on diseased cells (Zhou, 2023). Stimuli responsive nanomedicines are an important innovation and releasing their cargo only in response to specific biological or environmental triggers such as acidic pH, elevated enzyme levels, or temperature changes. This approach ensures that therapeutic action is confined to the disease site and reducing off target toxicity (Wang, 2023). Theranostic platforms combine therapeutic delivery with diagnostic imaging, creating systems that allow real time monitoring of treatment response (Ijaz et al., 2024). In neurology, nanoparticles have been engineered to traverse the BBB, opening new avenues for treating diseases such as Alzheimer's and Parkinson's (Dong et al., 2023). In oncology, multifunctional nanocarriers now co-deliver chemotherapy agents, gene therapy vectors and immunomodulators, thereby addressing tumor heterogeneity and resistance (Lammers et al., 2024). These innovations reflect a paradigm shift in healthcare toward interventions that are safer, more precise, and more adaptable to patient specific needs.

1.3 Scope and Significance of Nanomedicine in Drug Development

The scope of nanomedicine extends well beyond conventional drug delivery, encompassing diagnostics, imaging, regenerative medicine, and vaccine technology. Nanoparticles have been employed to deliver a broad spectrum of therapeutic molecules, including small drugs, peptides, small interfering ribonucleic acid (siRNA), messenger ribonucleic acid (mRNA) and clustered regularly interspaced short palindromic repeats (CRISPR) based systems (Moazzam et al., 2024; Vosoughi et al., 2025).

The global rollout of coronavirus disease 2019 (COVID-19) vaccines based on lipid nanoparticles demonstrated the scalability and transformative power of this technology (Hou et al., 2021). In diagnostics, quantum dots and nanosensors provide enhanced sensitivity, enabling earlier and more accurate disease detection (Durgam et al., 2025). Similarly, nanostructured scaffolds in tissue engineering guide cellular differentiation and repair and accelerating regenerative strategies (Alimohammadvand et al., 2024).

Nanomedicine is also central to the growth of personalized medicine. By tailoring nanoparticle formulations to patient-specific genetic or proteomic signatures, therapies can achieve greater efficacy with fewer adverse effects (Mao et al., 2024). Importantly, nanomedicine shortens the drug development cycle by facilitating combined diagnostic therapeutic approaches that yield faster feedback during clinical testing. While unresolved challenges remain particularly regarding safety, large scale manufacturing and regulatory approval the overall impact of nanomedicine on drug development is profound. It not only provides innovative options for diseases that have limited treatment choices but also redefines how medicines are conceived, tested and deployed in modern healthcare systems.

2. NANOCARRIER SYSTEMS IN DRUG DELIVERY

Nanocarrier systems constitute the core of modern drug delivery strategies which providing controlled transport and release of therapeutic agents. By manipulating nanoscale structures, researchers can optimize pharmacokinetics, improve solubility and achieve site specific targeting (Waheed et al., 2024). Nanocarriers also facilitate the delivery of complex molecules such as peptides, proteins, nucleic acids and siRNA (Ijaz et al., 2024). Figure 1 provides an overview of the major nanomedicine platforms, illustrating their structural diversity and functional applications. Table 1 summarizes representative nanocarrier systems, highlighting their characteristics, advantages, therapeutic applications and clinical development stage.

Table 1. Examples of nanocarrier systems in drug discovery and development

Nanocarrir type	Key features	Advantages	Therapeutc applicatios	Stage	Reference
Liposomes	Phospholipid bilayer vesicles; can encapsulate hydrophilic and hydrophobic drugs	Biocompatibility, controlled release, surface modification with ligands	Cancer chemotherapy, antifungals, vaccines	Several approved; many in clinical trials	Chelliah et al., 2024
Polymeric nanoparticle	Biodegradable polymers with tunable size and release kinetics	High stability, controlled degradation, Polyethylene glycolylation reduces clearance	siRNA delivery, protein and peptide drugs, oncology	Multiple in clinical and preclinical phases	Ding et al., 2024
Micelles	Amphiphilicblock copolymers self-assembled into core–shell nanostructures	Solubilization of poorly soluble drugs, easy synthesis	Delivery of paclitaxel, curcumin, photosensitizers	Preclinical and early clinical trials	Kuperkar et al., 2022
Nanoemulsions	Oil-in-water or water-in-oil colloidal dispersions	Enhance solubility, fast absorption, scalable	Oraldelivery of poorly solubledrugs, vaccines, nutraceutica	Clinical formulations under development	Preeti et al., 2023
Dendrimers	Branched, tree-like polymers with multivalent surface groups	High drug loading,surfacefunctionalization, gene delivery	Antiviral drugs, anticancer agents, gene therapy	Preclinical; some in clinical testing	Patil et al., 2024
Solid lipid nanoparticle	Solid lipid core stabilized by surfactants	Protect labiledrugs, controlled release, good stability	Delivery of anticancer and antidiabetic drugs	Preclinical and early clinical	Akanda et al., 2023

Nanocarrir type	Key features	Advantages	Therapeutc applicatios	Stage	Reference
Nanostructured lipid carriers	Blend of solid and liquid lipids	Higher drug loading, reduced drug expulsion, improved stability	Anti-inflammatory drugs, cosmetics, CNS delivery	Clinical formulations in development	Khan et al., 2023
Biomimetic nanocarriers (cell-membrane coated)	Nanoparticles cloaked with natural cell membranes (RBCs, platelets, cancer cells)	Immune evasion, prolonged circulation, targeted delivery	Oncology, cardiovascular diseases, immune modulation	Preclinical; some in early clinical trials	Feng et al., 2025; Zhao et al., 2025
Exosome-inspired nanocarriers	Natural extracellular vesicle mimetic	Intrinsic biocompatibility, cell-cell communication, nucleic acid delivery	Cancer therapy, regenerative medicine, neurological disorders	Rapidly emerging, mostly preclinical	Sen et al., 2023

2.1 Liposomes

Liposomes are vesicular systems composed of phospholipid bilayers capable of encapsulating both hydrophilic and hydrophobic drugs. Their structure allows compartmentalization of therapeutic molecules and protecting them from degradation during circulation (Agrawal et al., 2024). Liposomes can be surface modified with targeting ligands or PEG to enhance tissue specificity and extend circulation time. They exhibit passive targeting via the enhanced permeability and retention effect and active targeting through ligand mediated recognition of cellular receptors (Gatto et al., 2024; Jaradat et al., 2024). Clinically, liposomal formulations have been applied to cancer therapy, antifungal treatments and vaccine delivery and with several products such as Doxil®, successfully approved (Cheng et al., 2025). Despite these advantages, liposomes may present challenges including limited drug loading capacity, potential instability and manufacturing complexity (Agrawal et al., 2024).

Stimuli responsive liposomes are being developed to release drugs under defined environmental cues such as pH changes or enzymatic activity and increasing therapeutic precision (Torres et al., 2025).

2.2 Polymeric Nanoparticles

Polymeric nanoparticles are solid colloidal structures formulated from biodegradable polymers like Poly(lactic acid) and poly(lactic-co-glycolic) acid nanoparticles and PEG-based copolymers (Perinelli et al., 2019). Their design enables tunable release kinetics, high drug loading capacity and protection of labile molecules from enzymatic degradation (Khalbas et al., 2019). PEGylation reduces immune clearance and prolongs systemic circulation, improving delivery efficiency. Mechanistically, polymeric nanoparticles enter target cells via endocytosis, facilitating intracellular transport of drugs, proteins and nucleic acids. Applications include oncology, gene therapy and delivery of peptide or protein therapeutics. Limitations involve polymer toxicity at high doses, reproducibility issues in synthesis and scalability challenges for clinical production (Floyd et al., 2025). Advances in polymer chemistry are now focusing on multifunctional polymers capable of co-delivering multiple agents for combination therapy.

2.3 Micelles and Nanoemulsions

Micelles are self assembled amphiphilic block copolymers forming a hydrophobic core and hydrophilic shell which enabling encapsulation of poorly water soluble drugs (Honarmand et al., 2023). Nanoemulsions are colloidal dispersions of immiscible liquids stabilized by surfactants, which enhance solubility and absorption (Jadhav et al., 2024). Micelles have been used for delivery of chemotherapeutic agents, natural products and photosensitizers, whereas nanoemulsions have applications in oral, topical and parenteral drug administration (Chatzidaki et al., 2025). Both systems offer rapid drug release and improved bioavailability, yet they may face stability issues under physiological conditions and are generally limited in loading highly charged or large molecules. Optimization of surfactant composition and particle size distribution has enhanced their clinical applicability in recent studies (Sun et al., 2025; Verma et al., 2025).

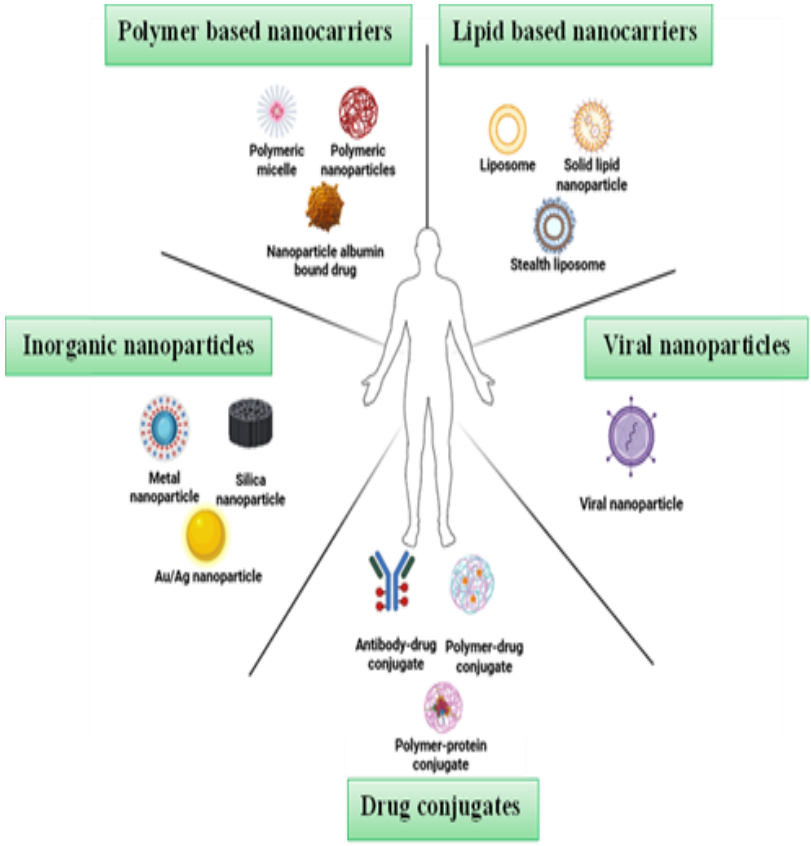


Figure 1. Schematic illustration of nanotherapeutics and nanomedicine platforms in modern medicine.

2.4 Dendrimers

Dendrimers are highly branched, monodisperse macromolecules with a defined core, interior branching layers and multiple terminal functional groups (Kaurav, 2023). These features enable high drug loading and precise control over molecular architecture (Fadaei et al., 2025). Drugs can be encapsulated in internal cavities or conjugated to the surface, allowing multifunctional delivery strategies (Alamos-Musre et al., 2025). Dendrimers have been investigated in antiviral therapy, oncology, and gene therapy, with surface functionalization providing selective targeting and improved cellular uptake (Fadaei et al., 2025). However, dendrimers may exhibit cytotoxicity at elevated concentrations, and their complex synthesis increases production costs (Kaurav, 2023).

Despite these limitations, dendrimers remain a versatile platform for engineering multifunctional therapeutic carriers (Mehta & Roy, 2024).

2.5 Lipid Based Nanocarriers

Solid lipid nanoparticles and nanostructured lipid carriers are lipid based systems designed for enhanced stability and controlled drug release (Viegas et al., 2023). Solid lipid nanoparticles consist of a solid lipid matrix stabilized by surfactants which providing protection for labile drugs and controlled release profiles (Waheed et al., 2024). Nanostructured lipid carriers incorporate a mixture of solid and liquid lipids to improve drug loading and minimize expulsion during storage (Mall et al., 2024). Lipid based carriers are particularly effective for hydrophobic drugs and are administered through oral, topical and parenteral routes (Kothapalli et al., 2024). Their utility has been demonstrated in delivering anticancer agents, anti-inflammatory drugs and mRNA vaccines (Xu et al., 2024). Limitations include potential polymorphic transitions affecting stability and limited loading of hydrophilic drugs. Research continues to optimize lipid composition and surface modification for enhanced therapeutic performance.

2.6 Biomimetic and Hybrid Nanocarriers

Biomimetic nanocarriers leverage natural cellular components to improve compatibility and targeting (Huang et al., 2023). Cell membrane coated nanoparticles involve cloaking synthetic particles with membranes from red blood cells, platelets, or tumor cells, conferring immune evasion and prolonged circulation (Liu et al., 2023). Exosome inspired carriers mimic natural extracellular vesicles and enable intercellular communication and providing efficient delivery of nucleic acids and proteins (Zhao et al., 2025). These systems have demonstrated potential in oncology, cardiovascular therapy and neurological disorders. However, challenges such as large scale production, standardization and potential immunogenicity remain. Biomimetic approaches represent a strategic evolution in nanomedicine and bridging the gap between synthetic materials and natural biological functionality.

2.7 Comparative Advantages and Limitations

Each nanocarrier type offers distinct benefits and constraints. Liposomes provide excellent biocompatibility but have moderate drug loading (Xu et al., 2024). Polymeric nanoparticles allow controlled release and multifunctional design but require careful attention to polymer toxicity and reproducibility (Fadaei et al., 2025). Micelles and nanoemulsions enhance solubility but face stability challenges (Sun et al., 2025). Dendrimers enable multivalent functionalization but involve complex synthesis (Kaurav, 2023). Lipid based carriers offer translational potential, whereas biomimetic and hybrid systems provide immune evasion and targeted delivery, although they are still largely preclinical (Huang et al., 2023). Table 1 offers a comprehensive comparison, emphasizing therapeutic applications and development stages. The choice of carrier depends on drug characteristics, desired pharmacokinetics, and the specific disease target. Combining multiple strategies into hybrid systems can overcome individual limitations and enhance therapeutic efficacy (Liu et al., 2023).

3. EMERGING CONCEPTS IN NANOMEDICINE

Nanomedicine continues to evolve beyond conventional drug delivery, incorporating advanced technologies that integrate therapy, diagnostics and real time health monitoring. The convergence of nanotechnology with precision medicine enables highly controlled interventions at the molecular and cellular level. Emerging concepts include theranostic systems, nanorobotics, stimuli responsive nanomaterials, gene editing nanocarriers and nanobiosensors. These approaches aim to enhance therapeutic efficacy, reduce systemic toxicity and provide personalized treatment solutions, marking a paradigm shift in modern healthcare.

3.1 Theranostics

Theranostics represents a synergistic platform that combines diagnostic and therapeutic capabilities within a single nanocarrier (Fahmy et al., 2025). These systems allow simultaneous detection of disease biomarkers and delivery of targeted therapy, facilitating real time monitoring of treatment outcomes.

For example, nanoparticles can be functionalized with imaging agents such as fluorophores, magnetic resonance imaging contrast agents, or radionuclides, while also carrying chemotherapeutics, siRNA, or immunomodulators (Karthikeyan et al., 2023). Theranostic systems enable early intervention, dose optimization, and evaluation of therapeutic response, particularly in oncology and cardiovascular diseases. Advantages include precise targeting, reduced off-target effects and improved clinical decision making. Challenges remain in balancing imaging sensitivity with therapeutic payload, regulatory approval, and scalable production. Recent studies demonstrate that multifunctional liposomes and polymeric nanoparticles can serve as theranostic agents, integrating molecular imaging with controlled drug release for personalized cancer treatment (Kelkar et al., 2011).

3.2 Nanorobotics

Nanorobotics involves the development of nanoscale machines capable of precise manipulation, sensing and actuation within biological systems (Antil & Gupta, 2024). These devices can navigate through vascular networks, recognize target cells and release therapeutic payloads with high spatiotemporal accuracy. Molecular motors, DNA origami based robots and magnetic or chemical propulsion systems are being explored for applications in targeted drug delivery, microsurgery and tissue repair (Jiang et al., 2023). The potential of nanorobots lies in their ability to access previously unreachable anatomical sites, perform complex intracellular operations and respond dynamically to physiological conditions. Despite promising in vitro and preclinical results, clinical translation is challenged by biocompatibility, immune clearance, power supply and real time control within living organisms (Pu et al., 2024).

3.3 Smart Nanomaterials and Stimuli Responsive Systems

Smart nanomaterials are engineered to respond to specific internal or external stimuli including pH, temperature, redox potential, enzymatic activity, or light (Wells et al., 2019). These stimuli responsive carriers enable controlled drug release precisely at the site of disease, reducing systemic exposure and enhancing therapeutic efficacy.

For instance, pH sensitive nanoparticles release payloads in acidic tumor microenvironments, while enzyme responsive systems exploit elevated protease activity in inflamed tissues (Bhattacharya et al., 2023; Mi et al., 2020). Temperature sensitive liposomes and polymeric hydrogels provide on demand release triggered by hyperthermia or external heating. Redox responsive carriers utilize intracellular glutathione gradients to trigger cytosolic drug release. These systems are highly relevant in oncology, infectious diseases and inflammatory conditions, as they allow temporal and spatial control of therapeutic activity. Challenges include ensuring stability in circulation, avoiding premature release and achieving reproducible manufacturing.

3.4 CRISPR and Gene Editing Nanocarriers

The integration of nanotechnology with CRISPR/Cas gene editing tools has enabled precise modulation of genetic sequences in target cells (Kazemian et al., 2022). Nanocarriers such as lipid nanoparticles, polymeric nanoparticles and dendrimers have been employed to deliver CRISPR components, including guide RNA and Cas proteins, efficiently and safely (Ashok et al., 2021). These carriers protect genetic payloads from enzymatic degradation, enhance cellular uptake and enable targeted gene editing in vivo. Applications include treatment of genetic disorders, cancer immunotherapy and antiviral strategies. Lipid nanoparticle based CRISPR delivery has demonstrated success in preclinical models for liver diseases and hematologic disorders (Baig et al., 2025). Despite rapid progress, challenges persist in off-target effects, immune activation, delivery efficiency and large scale translation.

3.5 Nanobiosensors and Real Time Health Monitoring

Nanobiosensors exploit nanoscale materials to detect biological signals with high sensitivity and specificity (Varadharajan et al., 2025). These devices integrate nanostructured transducers with recognition elements such as antibodies, aptamers, or enzymes to measure biomarkers in real time. Applications include continuous glucose monitoring, detection of infectious pathogens, cancer biomarker screening, and evaluation of therapeutic response (Chen et al., 2024).

Nanosensors enable minimally invasive or noninvasive monitoring, providing immediate feedback for personalized treatment adjustment. Integration with wearable devices and mobile platforms facilitates remote patient management and data-driven healthcare strategies. Current challenges involve sensor stability, biocompatibility, signal to noise optimization and regulatory approval (Gulati, 2025).

4. CLINICAL TRANSLATION AND REGULATORY CHALLENGES

The translation of nanomedicine from bench to bedside requires careful consideration of safety, reproducibility, stability, regulatory compliance and societal impact. Despite remarkable preclinical success, many promising nanotherapeutics face hurdles in clinical adoption due to the complexity of their design, potential toxicity and scale up challenges. Addressing these issues is critical to ensure that nanomedicine achieves its therapeutic potential in real world healthcare settings.

4.1 Safety and Toxicological Issues

Safety assessment remains a primary challenge in clinical translation. Nanoparticles possess unique physicochemical properties including high surface area to volume ratios, which may trigger unexpected biological interactions. Toxicity can manifest as oxidative stress, inflammation, immunogenic responses, or organ specific accumulation, depending on particle composition, size, surface charge and functionalization (Awashra, & Młynarz, 2023; Kim et al., 2025). As example, metallic nanoparticles such as gold or silver may cause cytotoxicity at higher doses, whereas lipid based carriers generally exhibit improved biocompatibility but require evaluation for long term effects (Gulati et al., 2025). Comprehensive in vitro and in vivo toxicological studies, including genotoxicity, hemocompatibility and immunotoxicity assessments, are necessary to predict human responses. Safety evaluation must also consider chronic exposure, repeated dosing and potential interactions with existing therapies (Xu et al., 2024).

4.2 Large Scale Production and Reproducibility

Scaling laboratory scale nanocarrier synthesis to industrial production poses significant challenges. Reproducibility in particle size, surface properties, drug loading and release profiles is critical to ensure consistent efficacy and safety. Techniques such as microfluidics, high pressure homogenization and self assembly methods have improved scalability, but batch to batch variation remains a concern (Lin et al., 2023).

Process control and quality assurance protocols must be rigorously implemented and Good Manufacturing Practices (GMP) compliance is essential (Mehta et al., 2023). Moreover, complex multifunctional or hybrid nanocarriers further complicate manufacturing due to multi step synthesis and functionalization requirements. Addressing these challenges is essential to facilitate regulatory approval and clinical deployment.

4.3 Stability and Storage Challenges

Nanomedicines are sensitive to environmental factors including temperature, light, pH and ionic strength, which may affect stability and shelf life (Mehta et al., 2023). Aggregation, precipitation, or degradation of nanocarriers can alter pharmacokinetics and reduce therapeutic efficacy (Gatto et al., 2023). Strategies to improve stability include lyophilization, cryoprotectants and incorporation of stabilizing excipients (Fonte et al., 2016). Lipid nanoparticles, for instance, may undergo polymorphic transitions over time, while polymeric nanoparticles may experience hydrolysis or polymer chain scission. Maintaining consistent drug loading and release kinetics during storage is critical for ensuring predictable clinical outcomes. Proper packaging, cold-chain logistics, and standardized storage conditions are necessary for commercialization and clinical application (Mehta et al., 2023).

4.4 Regulatory Frameworks

Regulatory approval is a key determinant of clinical translation. Agencies such as the U.S. Food and Drug Administration (FDA), European Medicines Agency (EMA) and International Council for Harmonisation (ICH) provide guidelines for evaluating quality, safety and efficacy of nanomedicines.

Regulatory scrutiny extends beyond conventional drug evaluation, addressing nanoparticle characterization, surface chemistry, biodistribution and long term safety (Rodríguez-Gómez et al., 2025). Standardized protocols for preclinical and clinical testing are still evolving and regulators often require extensive data on pharmacokinetics, immunogenicity and toxicology (Souto et al., 2024). Harmonization of global regulatory requirements remains a challenge due to variations in definitions, testing methodologies and product classification. Early engagement with regulatory bodies can accelerate translation and reduce delays in clinical trials.

4.5 Ethical and Societal Considerations

Ethical and societal issues are integral to the responsible development of nanomedicine. Concerns include long term human exposure, environmental impact, equitable access and informed consent in clinical studies. Public perception of nanotechnology in medicine influences adoption and transparent communication of risks and benefits is essential. Furthermore, intellectual property rights and data privacy in personalized nanomedicine require careful regulation. Ethical review committees and stakeholder engagement play a critical role in guiding clinical studies, ensuring patient safety and fostering public trust. Addressing these aspects is vital for integrating nanomedicine into mainstream healthcare without unintended social consequences.

5. CASE STUDIES AND CLINICAL APPLICATIONS

Nanomedicine has transitioned from theoretical research to tangible clinical interventions, providing new therapeutic options across oncology, infectious diseases and neurological disorders. Real world examples demonstrate how nanocarrier systems improve drug bioavailability, reduce systemic toxicity and enable precision therapy. Analysis of approved products and ongoing clinical trials highlights both successes and challenges, offering insights into translational strategies. Nanomedicine, particularly through targeted drug delivery and controlled release technologies, enhances therapeutic efficacy. Additionally, nanoparticle-based systems offer safer and more personalized treatment options, improving patients' quality of life.

5.1 Approved Nanomedicines

Several nanomedicines have received regulatory approval, illustrating the clinical potential of nanotechnology-based therapies. Doxil, a liposomal formulation of doxorubicin, reduces cardiotoxicity while maintaining antitumor efficacy in ovarian cancer and multiple myeloma patients (FDA, 1995). Abraxane, an albumin-bound paclitaxel nanoparticle, improves solubility and facilitates tumor uptake without toxic solvents, making it suitable for breast, lung, and pancreatic cancers (FDA, 2005). Onivyde, a liposomal irinotecan formulation, enhances pharmacokinetics and reduces gastrointestinal toxicity, offering improved outcomes in metastatic pancreatic cancer (FDA, 2024). These examples underscore the advantages of nanocarriers in modulating drug pharmacokinetics, protecting labile drugs, and enabling targeted delivery.

5.2 Nanomedicines in Cancer Therapy

Cancer therapy remains the most prominent application of nanomedicine. Nanocarriers can exploit the enhanced permeability and retention effect to accumulate selectively in tumor tissues (Pallares et al., 2025). Liposomes, polymeric nanoparticles, micelles and dendrimers have been evaluated for delivering chemotherapeutics, siRNA and immune modulators (Fan et al., 2023). Multifunctional nanocarriers facilitate combination therapy, co-delivering chemotherapy and gene silencing agents to overcome drug resistance. Recent clinical trials demonstrate improved response rates, reduced systemic toxicity and enhanced patient quality of life (Melo et al., 2025). Challenges include heterogeneity in tumor vasculature, variable enhanced permeability and retention effects and the need for predictive biomarkers to optimize patient selection.

5.3 Nanomedicine in Infectious Diseases and Vaccines

The rapid development of mRNA vaccines for COVID-19 highlighted the critical role of nanomedicine in infectious disease management. Lipid nanoparticles encapsulating mRNA provide protection from enzymatic degradation, facilitate cellular uptake and enable robust antigen expression, resulting in effective immune responses (Liu et al., 2024).

Similar strategies are being investigated for vaccines against influenza, RSV and emerging pathogens (Pilkington et al., 2021). Nanocarriers also improve pharmacokinetics and targeted delivery of antimicrobial agents, addressing challenges related to drug solubility, stability, and resistance (Hajiaghapour Asr et al., 2023). Clinical data demonstrate high efficacy and favorable safety profiles for these nanomedicine-based vaccines, emphasizing their transformative potential in global health.

5.4 Neurological Disorders and Targeted Delivery to the Brain

Neurological diseases present significant therapeutic challenges due to the BBB. Nanocarriers have been engineered to cross the BBB via receptor mediated transport, transcytosis, or temporary disruption strategies (Xie et al., 2019). Polymeric nanoparticles, liposomes and dendrimers have been employed to deliver chemotherapeutics, neuroprotective agents and gene editing constructs to the central nervous system (Romero-Ben et al., 2025). Preclinical studies report enhanced brain bioavailability, reduced systemic exposure and improved functional outcomes in models of Alzheimer's disease, Parkinson's disease and glioblastoma (Boyton et al., 2024; Krsek & Baticic, 2024) . Despite promising results, clinical translation requires rigorous safety evaluation and optimization of delivery efficiency.

5.5 Lessons From Clinical Trials

Clinical experience with nanomedicines emphasizes the importance of comprehensive preclinical assessment, patient selection and biomarker driven approaches. Variability in patient physiology, tumor microenvironment and immune response influences therapeutic outcomes. Trials highlight the need for reproducible manufacturing, stability under storage conditions and scalable production. Regulatory compliance, ethical conduct and transparent communication of risks and benefits remain central to successful translation. These lessons inform the design of next generation nanomedicines, which aim to combine targeted therapy, controlled release and personalized treatment strategies.

6. FUTURE PROSPECTS IN NANOMEDICINES

Nanomedicine is poised to redefine healthcare by integrating advanced materials, engineering, and biological understanding with emerging technological trends. Future prospects focus on personalized therapeutics, regenerative medicine, artificial intelligence (AI) enabled decision making, sustainable nanotechnology and novel diagnostic and monitoring platforms. These developments are expected to enhance precision, safety and accessibility of treatments while addressing global healthcare challenges.

As a real world example, the Sri Lanka Institute of Nanotechnology (SLINTEC) has recently established a dedicated nanomedicine activity monitoring laboratory. This facility is fully funded by the Sri Lankan government and is designed to evaluate the performance and biological activity of various nanomedicine formulations, providing critical insights into therapeutic efficacy and safety. Similar initiatives have been developed in other research centers worldwide, creating platforms for advanced diagnostic monitoring, in vivo imaging and real time assessment of nanoparticle behavior, which collectively accelerate the translation of nanomedicine innovations from laboratory research to clinical application.

6.1 Personalized and Precision Nanomedicine

Personalized nanomedicine leverages individual molecular, genetic and proteomic profiles to optimize therapy. Nanocarriers can be engineered for patient specific targeting by functionalizing with ligands that recognize tumor specific receptors, immune cell markers, or disease associated proteins. Theranostic nanoparticles facilitate simultaneous imaging and therapy, enabling real time monitoring of therapeutic outcomes and dose adjustments (Fan et al., 2023). Advances in genomics and bioinformatics allow tailoring of drug loaded nanoparticles to individual patients, improving efficacy and minimizing adverse effects (Mao, 2024). Integration with digital health tools and wearable nanosensors supports continuous monitoring of physiological parameters, allowing dynamic adjustment of treatment regimens. The combination of genetic tailoring, targeted delivery and in vivo diagnostics exemplifies the precision capabilities of future nanomedicine platforms.

6.2 Regenerative Nanomedicine and Tissue Engineering

Nanotechnology is increasingly applied in regenerative medicine to restore damaged tissues and organs. Nanoscale scaffolds composed of biomaterials such as hydroxyapatite, collagen, or biodegradable polymers guide cell adhesion, proliferation, and differentiation (Radha et al., 2023). Nanostructured hydrogels, fibers and microenvironments facilitate stem cell therapy and tissue regeneration by mimicking native extracellular matrices. Nanocarriers can deliver growth factors, nucleic acids, and small molecules in a controlled manner to promote tissue repair (Li et al., 2023). These approaches have been explored for cardiovascular repair, bone regeneration, neural tissue engineering, and wound healing. By combining biomaterials, stem cell therapy and controlled nanodelivery, regenerative nanomedicine provides innovative solutions for functional tissue reconstruction and organ regeneration.

6.3 Integration with AI and Digital Health

AI and machine learning are transforming nanomedicine design, diagnostics and clinical decision making. AI algorithms predict nanoparticle behavior, optimize drug release profiles, and identify molecular targets based on large scale omics and imaging data (Serrano et al., 2024). Integration with digital health platforms enables real time monitoring using nanosensors, lab on a chip systems and wearable devices. Continuous feedback loops between patient data and nanomedicine interventions allow adaptive therapies, enhancing precision and reducing systemic toxicity. AI assisted imaging, including in vivo ultrasounds, electron microscopy and optical spectroscopy, improves disease detection and monitors treatment response at the molecular level. Such convergence of nanotechnology and digital health is expected to accelerate personalized treatment and improve patient outcomes globally.

6.4 Sustainable Nanomedicine (Green Nanotechnology)

Sustainability is emerging as a critical consideration in nanomedicine development. Green nanotechnology emphasizes environmentally friendly synthesis methods, use of biocompatible and biodegradable materials and reduction of hazardous waste (Olaniyan et al., 2025).

Plant based extracts, microbial synthesis and solvent free methods are being explored to produce nanoparticles with minimal ecological impact. Sustainable nanomedicine not only addresses environmental concerns but also enhances safety and biocompatibility in clinical applications. Cost effective, scalable and green production strategies are crucial for global accessibility and equitable healthcare distribution. Such approaches align with the long term vision of nanomedicine as a responsible and widely applicable therapeutic platform.

6.5 Potential to Reshape Global Healthcare

Nanomedicine has the potential to fundamentally transform global healthcare by enabling advanced drug delivery, regenerative therapy, real time health monitoring and precision diagnostics. Figure 2 illustrates this integrated vision such as drug delivery platforms offer long circulation times and low systemic toxicity, regenerative therapies utilize biomaterials and stem cells, health monitoring relies on in vivo imaging, lab on a chip devices, nanobiosensors and microarrays, theranostics combines diagnostics with therapy for targeted delivery, nanorobotics performs molecular level cell repair and personalized medicine provides genetic tailoring and custom drugs. Collectively, these technologies promise more effective, safer and patient specific treatments while reducing treatment related morbidity. Furthermore, by facilitating early disease detection, monitoring therapeutic responses and delivering targeted interventions, nanomedicine can improve healthcare efficiency, reduce costs and expand access to precision medicine worldwide.

CONCLUSION

Nanomedicine is revolutionizing drug discovery by enabling precise, safe, and efficient therapy delivery. Nanoscale platforms liposomes, polymeric nanoparticles, micelles, dendrimers, and biomimetic carriers enhance stability, bioavailability and reduce side effects. Advanced systems such as theranostics, nanorobotics and AI assisted monitoring support personalized treatments and regenerative medicine.

Despite challenges in safety, biocompatibility, large scale production and regulatory approval, continuous innovation drives progress. Future directions emphasize smart, stimuli responsive systems, integration with genomics, green nanotechnology and advanced theranostics. By overcoming translational barriers, nanomedicine promises highly targeted, adaptive and patient focused therapies, transforming drug development and improving global healthcare outcomes.

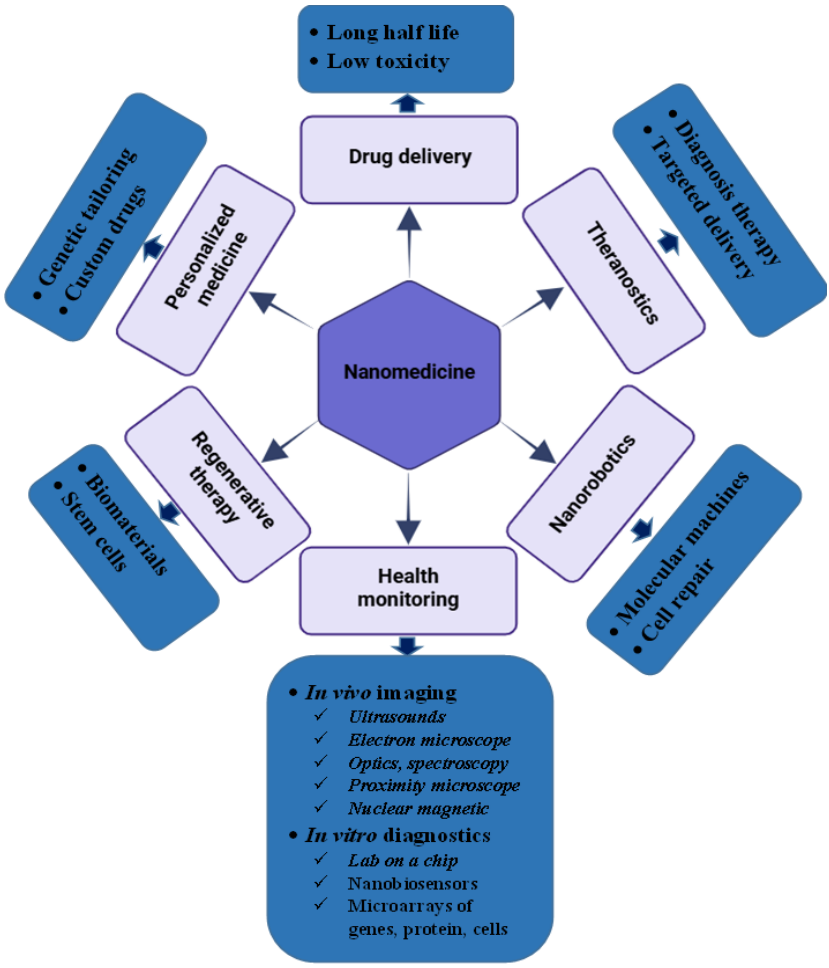


Figure 2. Emerging horizons of nanomedicine.

REFERENCES

Agrawal, S. S., Kumar, A., Patel, R., & Sharma, P. (2024). Liposomal formulations: A recent update. PubMed.

Akanda, M., Mithu, M. S. H., & Douroumis, D. (2023). Solid lipid nanoparticles: An effective lipid-based technology for cancer treatment. Journal of Drug Delivery Science and Technology, 86, 104709. https://doi.org/10.1016/j.jddst.2023.104709

Alamos-Musre, S., et al. (2025). From structure to function: The promise of PAMAM dendrimers in drug delivery. Pharmaceutics, 17(1), 1-14. https://doi.org/10.3390/pharmaceutics17010001

Alfutaimani, A. S., Alharbi, N. K., S Alahmari, A., A Alqabbani, A., & Aldayel, A. M. (2024). Exploring the landscape of Lipid Nanoparticles (LNPs): A comprehensive review of LNPs types and biological sources of lipids. International journal of pharmaceutics: X, 8, 100305.

Alimohammadvand, S., Zenjanab, K., Mashinchian, M., Shayegh, J., & Jahanban-Esfahlan, R. (2024). Recent advances in biomimetic cell membrane-camouflaged nanoparticles for cancer therapy. Biomedicine & Pharmacotherapy, 177, 116951.

Antil, M., & Gupta, V. (2024). Nanorobots in medicine: Advancing healthcare through molecular engineering: A comprehensive review. IgMin Research, 2(11), 938–949. https://doi.org/10.61927/igmin271

Ashok, B., Peppas, N. A., & Wechsler, M. E. (2021). Lipid- and polymer-based nanoparticle systems for the delivery of CRISPR/Cas9. Journal of Drug Delivery Science and Technology, 65, 102728.

Awashra, M., & Młynarz, P. (2023). The toxicity of nanoparticles and their interaction with cells: an in vitro metabolomic perspective. Nanoscale advances, 5(10), 2674–2723. https://doi.org/10.1039/d2na00534d

Baig, M. M. F. A., Chien, W. T., & Chair, S. Y. (2025). Nanotechnological approaches for the targeted delivery of CRISPR-Cas systems for genomic modifications, biomolecular sensing, and precision medicine. Biomaterials Science, 13(17), 4597–4638.

Bertrand, N. (2013). Cancer nanotechnology: The impact of passive and active targeting in the era of personalized medicine. Frontiers in Pharmacology, 4, 1–11. https://pmc.ncbi.nlm.nih.gov/articles/PMC4219254/

Bhattacharya, S., Gupta, A., & Sharma, S. (2023). A critical review on the dissemination of pH and stimuli-responsive polymeric nanocarriers for targeted drug distribution. Journal of Drug Delivery Science and Technology, 77, 103788. https://doi.org/10.1016/j.jddst.2023.103788

Boyton, I., Valenzuela, S. M., Collins-Praino, L. E., & Care, A. (2024). Neuronanomedicine for Alzheimer's and Parkinson's disease: Current progress and a guide to improve clinical translation. Brain, Behavior, and Immunity, 115, 631–651. https://doi.org/10.1016/j.bbi.2023.11.004

Bukke, S. P. N., Ramesh, P., & Kumar, A. (2024). Solid lipid nanocarriers for drug delivery. SN Applied Sciences, 6(1), 1-15.

Chatzidaki, M. D., Papadopoulos, A., & Karamanos, N. K. (2025). Advancements in nanoemulsion-based drug delivery. Pharmaceuticals, 18(1), 1-19. https://doi.org/10.3390/ph18010001

Chelliah, R., Rubab, M., Vijayalakshmi, S., Karuvelan, M., Barathikannan, K., & Oh, D.-H. (2025). Liposomes for drug delivery: Classification, therapeutic applications, and limitations. Next Nanotechnology, 8, 100209. https://doi.org/10.1016/j.nxnano.2025.100209

Chen, X., Liu, Y., & Wang, Z. (2024). Wearable biosensors for cardiovascular monitoring leveraging nanomaterials. Advanced Composites and Hybrid Materials, 7, Article 97. https://doi.org/10.1007/s42114-024-00906-6

Cheng, Z., Li, X., Wang, Y., & Zhang, H. (2025). Applications of liposomes and lipid nanoparticles in cancer therapy. BMC Medicine, 23(1), 102. https://doi.org/10.1186/s40164-025-00602-1

Ding, L., Agrawal, P., Singh, S. K., Chhonker, Y. S., Sun, J., & Murry, D. J. (2024). Polymer-Based Drug Delivery Systems for Cancer Therapeutics. Polymers, 16(6), 843. https://doi.org/10.3390/polym16060843

Dong, N. (2023). Nanomedicine in the treatment of Alzheimer's disease. Journal of Alzheimer's Disease, 90(2), 331-345.

Durgam, L. K., & Oroszi, T. L. (2025). Revolutionizing healthcare: the transformative potential of nanotechnology in medicine. Frontiers in drug delivery, 5, 1556426. https://doi.org/10.3389/fddev.2025.1556426

Fadaei, M. R., et al. (2025). Overview of dendrimers as promising drug delivery systems. Journal of Drug Delivery Science and Technology, 65, 102-115. https://doi.org/10.1016/j.jddst.2025.102115

Fahmy, H. M., Bayoumi, L., Helal, N. F., Mohamed, N. R. A., Emarh, Y., & Ahmed, A. M. (2025). Emerging trends in nano-theranostics: Integrating imaging and therapy for precision health care. International Journal of Pharmaceutics, 683, 126057.

Fan, D., Cao, Y., Cao, M., Wang, Y., Cao, Y., & Gong, T. (2023). Nanomedicine in cancer therapy. Signal Transduction and Targeted Therapy, 8, 293. https://doi.org/10.1038/s41392-023-01501-1

Feng, J., He, D., Chen, J., Li, M., Luo, J., Han, Y., Wei, X., Ren, S., Wang, Z., Wu, Y., Wang, H., Zhang, Y., & Zhou, Y. (2025). Cell membrane biomimetic nanoplatforms: A new strategy for immune escape and precision targeted therapy. Materials Today Bio, 35, 102343. https://doi.org/10.1016/j.mtbio.2025.102343

Floyd, T. G., Gurnani, P., & Rho, J. Y. (2025). Characterisation of polymeric nanoparticles for drug delivery. Nanoscale, 17(13), 7738-7752.

Fonte, P., Reis, S., & Sarmento, B. (2016). Facts and evidences on the lyophilization of polymeric nanoparticles for drug delivery. Journal of controlled release : official journal of the Controlled Release Society, 225, 75–86. https://doi.org/10.1016/j.jconrel.2016.01.034

Gatto, M. S., & Najahi-Missaoui, W. (2023). Lyophilization of Nanoparticles, Does It Really Work? Overview of the Current Status and Challenges. International journal of molecular sciences, 24(18), 14041.

Gatto, M. S., Rossi, F., & Bianchi, A. (2024). Targeted liposomal drug delivery: Overview of the current strategies. Life, 14(6), 672. https://doi.org/10.3390/life14060672

Gulati, S., Yadav, R., Kumari, V., Nair, S., Gupta, C., & Aishwari, M. (2025). Nanosensors in healthcare: Transforming real-time monitoring and disease management with cutting-edge nanotechnology. RSC Pharmaceutics, 2(4), 1003–1018. https://doi.org/10.1039/D5PM00125K

Hajiaghapour Asr, M., Dayani, F., Saedi Segherloo, F., Kamedi, A., Neill, A. O., MacLoughlin, R., & Doroudian, M. (2023). Lipid Nanoparticles as Promising Carriers for mRNA Vaccines for Viral Lung Infections. Pharmaceutics, 15(4), 1127.

Honarmand, S., Ramezani, M., & Farahani, M. (2023). Micelles-based systems and their versatile application in various fields. Journal of Nanoscience and Technology, 10(1), 1-15. https://doi.org/10.1016/j.jnst.2023.01.001

Hou, X., Zaks, T., Langer, R., & Dong, Y. (2021). Lipid nanoparticles for mRNA delivery. Nature Reviews Materials, 6, 1078–1094. https://doi.org/10.1038/s41578-021-00358-0

Huang, X., Li, M., & Zhang, Y. (2023). Biomimetic cell membrane-coated nanocarriers for targeted siRNA delivery in cancer therapy. Frontiers in Pharmacology, 14, 1234. https://doi.org/10.3389/fphar.2023.1234

Ijaz, M., Aslam, B., Hasan, I., Ullah, Z., Roy, S., & Guo, B. (2024). Cell membrane-coated biomimetic nanomedicines: Productive cancer theranostic tools. Biomaterials Science, 12(4), 863-895. https://doi.org/10.1039/D3BM01552A

Jadhav, S. P., Patil, R. D., & Kulkarni, S. S. (2024). Nanoemulsions: A versatile platform for enhanced drug delivery systems. International Journal of Advanced Research, 12(3), 1-15.

Jaradat, E., Al-Rashdan, A., & Mahmoud, H. (2024). Conventional vs PEGylated loaded liposomal formulations. International Journal of Pharmaceutics, 620, 122955.

Jiang, Q., Shang, Y., Xie, Y., & Ding, B. (2023). DNA origami: From molecular folding art to drug delivery technology. Advanced Materials. https://doi.org/10.1002/adma.202301035

Karthikeyan, L., Sobhana, S., Yasothamani, V., Gowsalya, K., & Vivek, R. (2023). Multifunctional theranostic nanomedicines for cancer treatment: Recent progress and challenges. Biomedical Engineering Advances, 5, 100082. https://doi.org/10.1016/j.bea.2023.100082

Kaurav, M. (2023). Dendrimer: An update on recent developments and future perspectives. Frontiers in Pharmacology, 14, 1159131.

Kazemian, P., et al. (2022). Lipid-nanoparticle-based delivery of CRISPR/Cas9 genome editing components. Molecular Pharmaceutics, 19(2), 457–469. https://doi.org/10.1021/acs.molpharmaceut.1c00916

Kelkar, S. S., & Reineke, T. M. (2011). Theranostics: Combining imaging and therapy. Bioconjugate Chemistry, 22(10), 1879–1903. https://doi.org/10.1021/bc200151q

Khalbas, A. H., Albayati, T. M., Ali, N. S., & Salih, I. K. (2024). Drug loading methods and kinetic release models using mesoporous silica nanoparticles as a drug delivery system: A review. South African Journal of Chemical Engineering, 50, 261-280.

Khan, S., Sharma, A., & Jain, V. (2023). An Overview of Nanostructured Lipid Carriers and its Application in Drug Delivery through Different Routes. Advanced pharmaceutical bulletin, 13(3), 446–460. https://doi.org/10.34172/apb.2023.056

Kim, E. H., Park, S., & Bae, O. N. (2025). Cardiovascular Toxicity of Metal-Based Nanoparticles. International journal of molecular sciences, 26(12), 5816. https://doi.org/10.3390/ijms26125816

Kothapalli, P., Reddy, S., & Sharma, V. (2024). Lipid-based nanocarriers for enhanced delivery of plant-derived bioactive compounds. Pharmaceuticals, 17(3), 329. https://doi.org/10.3390/ph17030329

Krsek, A., & Baticic, L. (2024). Nanotechnology-Driven Therapeutic Innovations in Neurodegenerative Disorders: A Focus on Alzheimer's and Parkinson's Disease. Future Pharmacology, 4(2), 352-379. https://doi.org/10.3390/futurepharmacol4020020

Kuperkar, K., Patel, D., Atanase, L., & Bahadur, P. (2022). Amphiphilic block copolymers: Their structures, and self-assembly to polymeric micelles and polymersomes as drug delivery vehicles. Polymers, 14, 4702. https://doi.org/10.3390/polym14214702

Lammers, T. (2024). Nanomedicine tumor targeting the advanced portfolio. Advanced Materials, 36(12), 2216-2234.

Li, Y., Xu, C., & Lei, C. (2023). The Delivery and Activation of Growth Factors Using Nanomaterials for Bone Repair. Pharmaceutics, 15(3), 1017. https://doi.org/10.3390/pharmaceutics15031017

Lin, H., Leng, J., Fan, P., Xu, Z., & Ruan, G. (2023). Scalable production of microscopic particles for biological delivery. Materials Advances, 4(14), 2885–2908. https://doi.org/10.1039/D3MA00021D

Liu, X., Xiao, C., & Xiao, K. (2023). Engineered extracellular vesicles-like biomimetic nanoparticles as an emerging platform for targeted cancer therapy. Journal of Nanobiotechnology, 21, 287. https://doi.org/10.1186/s12951-023-02064-1

Liu, Y., Huang, Y., He, G., Guo, C., Dong, J., & Wu, L. (2024). Development of mRNA Lipid Nanoparticles: Targeting and Therapeutic Aspects. International journal of molecular sciences, 25(18), 10166. https://doi.org/10.3390/ijms251810166

Lunardi, F., & Kwon, S. (2024). Chapter: Lipid Nanocarriers (in "Lipid based nanocarriers for drug delivery"). In New Developments in Nanotechnology Research. https://doi.org/10.52305/YLBA0323

Mall, J., Singh, A., & Verma, R. (2024). Nanostructured lipid carriers as a drug delivery system. Journal of Drug Delivery Science and Technology, 74, 102-115. https://doi.org/10.1016/j.jddst.2024.102115

Mao, Y., Xie, J., Yang, F., Luo, Y., Du, J., & Xiang, H. (2024). Advances and prospects of precision nanomedicine in personalized tumor theranostics. Frontiers in Cell and Developmental Biology, 12, 1514399. https://doi.org/10.3389/fcell.2024.1514399

Mehta, M., Bui, T. A., Yang, X., Aksoy, Y., Goldys, E. M., & Deng, W. (2023). Lipid-based nanoparticles for drug/gene delivery: An overview of the production techniques and difficulties encountered in their industrial development. ACS Materials Au, 3(6), 600–619. https://doi.org/10.1021/acsmaterialsau.3c00032

Melo, M. N., Amaral, R. G., Melo de Andrade, L. R., Severino, P., Blanco-Llamero, C., Andrade, L. N., & Souto, E. B. (2025). An overview of randomized phase III clinical trials of cancer nanomedicines. Cancer Pathogenesis and Therapy, 3(4), 322–336.

Mi P. (2020). Stimuli-responsive nanocarriers for drug delivery, tumor imaging, therapy and theranostics. Theranostics, 10(10), 4557–4588.

Moazzam, M., Zhang, M., Hussain, A., Yu, X., Huang, J., & Huang, Y. (2024). The landscape of nanoparticle-based siRNA delivery and therapeutic development. Molecular therapy : the journal of the American Society of Gene Therapy, 32(2), 284-312.

Olaniyan, Olawale F., Ariwaodo, Chinenye Agnes, Ibrahim, Sulyman Olalekan, Atolani, Olubunmi, & Kambizi, Learnmore. (2025). Advances in green synthesis and application of nanoparticles from crop residues: A comprehensive review. Scientific African, 28, e02654. https://doi.org/10.1016/j.sciaf.2025.e02654

Pallares, R. M., Barmin, R. A., Wang, A., Kiessling, F., & Lammers, T. (2025). Clinical cancer nanomedicines. Journal of Controlled Release, 385, 113991. https://doi.org/10.1016/j.jconrel.2025.113991

Patil, G., Patil, P., Kakde, R. A., Patil, L., Nikum, Y. P., Channwal, A., Hendve, K., Baviskar, R., & Patil, K. (2024). Dendrimers: A new class of polymer in drug delivery system; synthesis and application. World Journal of Advanced Research and Reviews, 23, 797-810.

Perinelli, D., Cespi, M., Bonacucina, G., & Palmieri, G. (2019). PEGylated polylactide (PLA) and poly(lactic-co-glycolic acid) (PLGA) copolymers for the design of drug delivery systems. Journal of Pharmaceutical Investigation, 49, 1-13. https://doi.org/10.1007/s40005-019-00442-2

Pilkington, E. H., Suys, E. J. A., Trevaskis, N. L., Wheatley, A. K., Zukancic, D., Algarni, A., Al-Wassiti, H., Davis, T. P., Pouton, C. W., Kent, S. J., & Truong, N. P. (2021). From influenza to COVID-19: Lipid nanoparticle mRNA vaccines at the frontiers of infectious diseases. Acta biomaterialia, 131, 16–40. https://doi.org/10.1016/j.actbio.2021.06.023

Preeti, Sambhakar, S., Malik, R., Bhatia, S., Al Harrasi, A., Rani, C., Saharan, R., Kumar, S., Geeta, & Sehrawat, R. (2023). Nanoemulsion: An Emerging Novel Technology for Improving the Bioavailability of Drugs. Scientifica, 2023, 6640103. https://doi.org/10.1155/2023/6640103

Pu, R., Yang, X., Mu, H., Xu, Z., & He, J. (2024). Current status and future application of electrically controlled micro/nanorobots in biomedicine. Frontiers in bioengineering and biotechnology, 12, 1353660. https://doi.org/10.3389/fbioe.2024.1353660

Radha, G., Manjubaashini, N., & Balakumar, S. (2023). Nano-hydroxyapatite/natural polymer composite scaffolds for bone tissue engineering: a brief review of recent trend. In vitro models, 2(5), 125–151. https://doi.org/10.1007/s44164-023-00049-w

Rodríguez-Gómez, F. D., Monferrer, D., Penon, O., & Rivera-Gil, P. (2025). Regulatory pathways and guidelines for nanotechnology-enabled health products: A comparative review of EU and US frameworks. Frontiers in Medicine, 12, Article 1544393.

Romero-Ben, E., Goswami, U., Soto-Cruz, J., Mansoori-Kermani, A., Mishra, D., Martin-Saldaña, S., Muñoz-Ugartemendia, J., Sosnik, A., Calderón,

M., Beloqui, A., & Larrañaga, A. (2025). Polymer-based nanocarriers to transport therapeutic biomacromolecules across the blood-brain barrier. Acta Biomaterialia, 196, 17–49.

Sen, S., Xavier, J., Kumar, N., Ahmad, M. Z., & Ranjan, O. P. (2023). Exosomes as natural nanocarrier-based drug delivery system: recent insights and future perspectives. 3 Biotech, 13(3), 101.

Serrano, D. R., Luciano, F. C., Anaya, B. J., Ongoren, B., Kara, A., Molina, G., Ramirez, B. I., Sánchez-Guirales, S. A., Simon, J. A., Tomietto, G., Rapti, C., Ruiz, H. K., Rawat, S., Kumar, D., & Lalatsa, A. (2024). Artificial Intelligence (AI) Applications in Drug Discovery and Drug Delivery: Revolutionizing Personalized Medicine. Pharmaceutics, 16(10), 1328. https://doi.org/10.3390/pharmaceutics16101328

Souto, E. B., Blanco-Llamero, C., Krambeck, K., Kiran, N. S., Yashaswini, C., Postwala, H., Severino, P., Priefer, R., Prajapati, B. G., & Maheshwari, R. (2024). Regulatory insights into nanomedicine and gene vaccine innovation: Safety assessment, challenges, and regulatory perspectives. Acta biomaterialia, 180, 1–17.

Sun, G., Li, X., & Wang, Y. (2025). The current status, hotspots, and development trends of nanoemulsions in drug delivery. Frontiers in Pharmacology, 16, 11910037.

Torres, J., Silva, R., & Martínez, P. (2025). Innovations in cancer therapy: Endogenous stimuli-responsive liposomal nanocarriers. Pharmaceutics, 17(2), 245. https://doi.org/10.3390/pharmaceutics17020245

U.S. Food and Drug Administration. (1995). Doxil® (doxorubicin HCl liposome injection) for intravenous infusion.

U.S. Food and Drug Administration. (2005). Abraxane® (paclitaxel protein-bound particles for injectable suspension) for intravenous use. https://www.drugs.com/history/abraxane.html

U.S. Food and Drug Administration. (2024). FDA approves irinotecan liposome for first-line treatment of metastatic pancreatic adenocarcinoma. https://www.fda.gov/drugs/resources- information-approved-drugs/fda-approves-irinotecan-liposome-first-line-treatment-metastatic-pancreatic-adenocarcinoma

Vaisman-Mentesh, A., Gutierrez-Gonzalez, M., DeKosky, B. J., & Wine, Y. (2020). The Molecular Mechanisms That Underlie the Immune Biology of Anti-drug Antibody Formation Following Treatment With Monoclonal Antibodies. Frontiers in immunology, 11, 1951.

Varadharajan, S., Gadre, M., Mathur, V., & Vasanthan, K. S. (2025). Sustainable integration of nanobiosensors in biomedical and civil engineering: A comprehensive review. ACS Omega, 10(24), 25120–25157. https://doi.org/10.1021/acsomega.5c00852

Verma, S., Sharma, P., & Gupta, R. (2025). Micelles transforming modern medicine. Progress in Nanomedicine, 9(2), 45-60.

Viegas, C., Pereira, M., & Silva, L. (2023). Solid lipid nanoparticles vs. nanostructured lipid carriers. Pharmaceuticals, 15(6), 1593.

Vosoughi, P., Naghib, S. M., Kangarshahi, B. M., & Mozafari, M. R. (2025). A review of RNA nanoparticles for drug/gene/protein delivery in advanced therapies: Current state and future prospects. International Journal of Biological Macromolecules, 295, 139532.

Waheed, I., Ali, A., Tabassum, H., Khatoon, N., Lai, W.-F., & Zhou, X. (2024). Lipid-based nanoparticles as drug delivery carriers for cancer therapy. Frontiers in Oncology, 14, 1296091.

Wang, T. (2023). Stimuli-responsive nanocarrier delivery systems for platinum-based anticancer drugs. RSC Advances, 13(1), 1-15. https://pubs.rsc.org/en/content/articlehtml/2023/ra/d3ra00866e

Wells, C. M., Harris, M., Choi, L., Murali, V. P., Guerra, F. D., & Jennings, J. A. (2019). Stimuli-responsive drug release from smart polymers. Journal of Functional Biomaterials, 10(3), 34.

Wu, K., Kwon, S. H., Zhou, X., Fuller, C., Wang, X., Vadgama, J., & Wu, Y. (2024). Overcoming Challenges in Small-Molecule Drug Bioavailability: A Review of Key Factors and Approaches. International Journal of Molecular Sciences, 25(23), 13121.

Xie, J., Shen, Z., Anraku, Y., Kataoka, K., & Chen, X. (2019). Nanomaterial-based blood-brain-barrier (BBB) crossing strategies. Biomaterials, 224, 119491. https://doi.org/10.1016/j.biomaterials.2019.119491

Xu, Y., Michalowski, C. B., Koehler, J., Darwish, T., Guccio, N., Alcaino, C., Domingues, I., Zhang, W., Marotti, V., Van Hul, M., Paone, P.,

Koutsoviti, M., Boyd, B. J., Drucker, D. J., Cani, P. D., Reimann, F., Gribble, F. M., & Beloqui, A. (2024). Smart control lipid-based nanocarriers for fine-tuning gut hormone secretion. Science advances, 10(50), eadq9909. https://doi.org/10.1126/sciadv.adq9909

Yun, Y., An, J., Kim, H. J., Choi, H. K., & Cho, H. Y. (2025). Recent advances in functional lipid-based nanomedicines as drug carriers for organ-specific delivery. Nanoscale, 17(13), 7617–7638.

Zhang, X., Fu, M., Wang, Y., & Wu, T. (2025). Strategies for delivering drugs across the blood-brain barrier for the treatment of neurodegenerative diseases. Frontiers in Drug Delivery, 5, 1644633.

Zhao, X., Chen, W., Wu, J., Shen, Y., Xu, B., Chen, Z., & Sun, Y. (2025). Application of Biomimetic Cell Membrane-Coated Nanocarriers in Cardiovascular Diseases. International journal of nanomedicine, 20, 8249–8289. https://doi.org/10.2147/IJN.S531558

Zhao, X., Li, J., & Wang, Z. (2025). Application of biomimetic cell membrane-coated nanocarriers in cardiovascular drug delivery. International Journal of Nanomedicine, 20, 567–580. https://doi.org/10.2147/IJN.S123456

Zhou, H. (2023). Stimuli-responsive nanotechnology for RNA delivery. Advanced Science, 10(6), 2303597.

ISBN: 978-625-93102-1-3