

## Industrial Biotechnology: Advancements in Sustainable Manufacturing and Production

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**Abstract:** Industrial biotechnology, an interdisciplinary field, employs biological systems to develop solutions for various industrial applications. This review traces its historical development from ancient fermentation to modern genetic engineering and bioprocessing technologies. Foundational concepts like microbial fermentation, enzyme and metabolic engineering, and biosensors are detailed, emphasizing their roles in sustainable production. Exploring applications across sectors like pharmaceuticals, agriculture, energy, and healthcare, biotechnological innovations enhance crop improvement, pest control, bioprocessing, and biopharmaceutical production, advancing food security and healthcare outcomes. Highlighting sustainability and environmental impact, industrial biotechnology reduces fossil resource dependency, minimizes waste, and mitigates carbon emissions. Challenges and opportunities in sustainable development underscore the need for ongoing research and collaboration. In conclusion, industrial biotechnology offers promise in addressing societal challenges and fostering a sustainable future, driven by nature-inspired innovation and interdisciplinary collaboration.

**Keywords:** Industrial biotechnology, Sustainability, Bioprocessing, Interdisciplinary

### 1. Introduction to Industrial Biotechnology

Industrial biotechnology is a branch of biotechnology that utilizes biological systems, organisms, or derivatives thereof to develop products and processes for various industrial applications. It represents a convergence of biology, chemistry, and engineering, aiming to harness the power of nature to drive sustainable manufacturing and production.

#### 1.1 Definition and Overview of Industrial Biotechnology

Industrial biotechnology involves the application of biological principles and processes to industrial production. It encompasses a wide range of disciplines, including microbiology, molecular biology, and biochemical engineering [1]. Within the realm of industrial biotechnology, the marriage of scientific disciplines serves as a catalyst for innovation, unlocking the potential of nature's blueprints to engineer novel solutions. By delving into the intricate workings of living organisms and molecular processes, researchers and practitioners alike navigate the complex tapestry of biological intricacies to craft bespoke solutions tailored to industrial needs. At its core, industrial biotechnology embodies a philosophy of synergy, where the fusion of biological principles with engineering prowess begets a paradigm shift in industrial methodologies. This interdisciplinary

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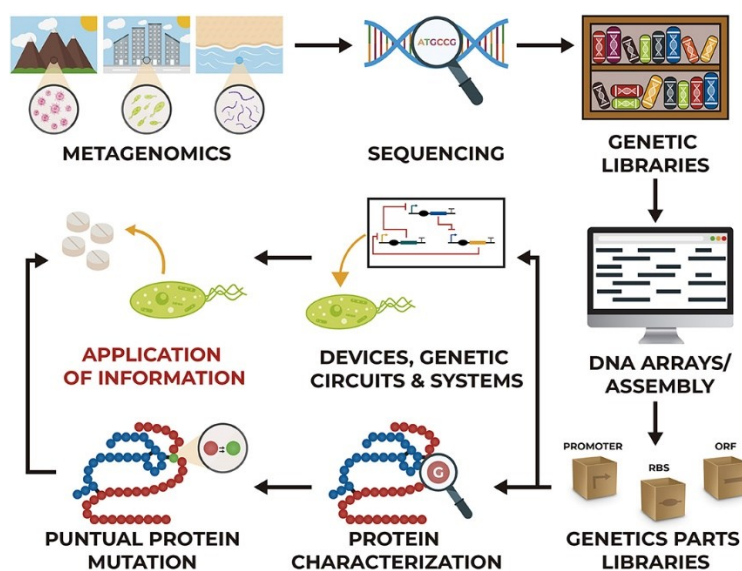
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approach not only fosters greater efficiency but also mitigates environmental impact, paving the way for a more sustainable future.

### 1.2 Historical Development of Industrial Biotechnology

The roots of industrial biotechnology can be traced back to ancient fermentation processes, such as the production of bread, beer, and wine. However, modern industrial biotechnology emerged in the late 20th century with the advent of genetic engineering and bioprocessing technologies [2], as shown in Figure 1. With the ability to genetically modify organisms and engineer novel biochemical pathways, researchers unlocked the potential for tailored solutions to industrial challenges. From the production of biofuels and biopolymers to the synthesis of pharmaceuticals and specialty chemicals, the scope of industrial biotechnology expanded exponentially, reshaping the landscape of modern industry. The journey of industrial biotechnology is one of continual evolution, characterized by a relentless pursuit of innovation and discovery. With each passing milestone, the boundaries of what is achievable are pushed ever further, fueled by the collective ingenuity of scientific minds around the globe.



**Figure 1.** Different stages for the development of synthetic biology and metabolic engineering projects [2].

### 1.3 Importance and Applications of Industrial Biotechnology

Industrial biotechnology has revolutionized various sectors, including pharmaceuticals, agriculture, energy, and chemicals. Its applications range from the production of biofuels and bioplastics to the synthesis of pharmaceuticals and industrial enzymes [3]. In the realm of pharmaceuticals, industrial biotechnology has ushered in a new era of drug discovery and development. From the synthesis of complex biologics to the production of life-saving vaccines, its contributions to the healthcare industry are immeasurable. By harnessing the power of genetic engineering and bioprocessing, researchers can expedite the production of therapeutic proteins and antibodies, paving the way for more accessible and affordable treatments for a myriad of diseases. In agriculture, industrial biotechnology plays a pivotal role in enhancing crop yields, improving nutritional content, and mitigating environmental impact. Through the development of genetically modified crops and biopesticides, it offers sustainable solutions to pest management and crop protection, reducing the reliance on harmful chemical inputs while ensuring food security for a

growing global population.

## 2. Key Technologies and Methods in Industrial Biotechnology

To achieve sustainable manufacturing and production goals, industrial biotechnology relies on a variety of technologies and methods.

### 2.1 Microbial Fermentation Technology

Microbial fermentation is a cornerstone of industrial biotechnology, involving the use of microorganisms to produce valuable products such as ethanol, organic acids, and enzymes. Advances in fermentation technology have enabled the efficient conversion of renewable feedstocks into bio-based products [4]. The importance of microbial fermentation within industrial biotechnology cannot be overstated. By tapping into the metabolic potential of microorganisms, researchers and engineers can unlock a treasure trove of bio-based products with far-reaching implications. Ethanol, a key component of biofuels, serves as a prime example, offering a renewable alternative to traditional fossil fuels and mitigating greenhouse gas emissions. Moreover, organic acids produced through microbial fermentation find widespread use in food preservation, pharmaceuticals, and chemical synthesis, contributing to the development of sustainable manufacturing processes. Advances in fermentation technology have propelled the efficiency and versatility of microbial fermentation to unprecedented heights. Through the integration of cutting-edge bioprocessing methodologies and genetic engineering techniques, researchers have optimized fermentation processes for enhanced productivity and yield. This has facilitated the efficient conversion of renewable feedstocks, such as agricultural residues and industrial waste streams, into a diverse array of bio-based products. By maximizing resource utilization and minimizing waste generation, microbial fermentation serves as a linchpin in the transition towards a circular economy model, where sustainability and economic viability go hand in hand.

### 2.2 Enzyme Engineering and Protein Engineering

Enzymes play a crucial role in industrial biotechnology, catalyzing biochemical reactions with high specificity and efficiency. Enzyme engineering techniques, such as directed evolution and rational design, allow for the optimization of enzyme properties for industrial applications. Similarly, protein engineering approaches enable the design of novel proteins with tailored functions and properties [5]. The significance of enzymes in industrial biotechnology transcends mere utility; it embodies a paradigm shift towards greener, more efficient manufacturing practices. Through the judicious application of enzyme engineering techniques, such as directed evolution and rational design, researchers unlock the full potential of these molecular workhorses. Directed evolution harnesses the power of iterative selection to fine-tune enzyme properties, enhancing substrate specificity, stability, and catalytic efficiency. Conversely, rational design leverages computational modeling and structural insights to engineer enzymes with tailored functionalities, ensuring optimal performance in industrial settings. The applications of enzyme engineering extend across a myriad of industries, each harnessing the unique capabilities of these biocatalysts to drive innovation and progress. In the realm of biofuels, enzymes play a central role in the conversion of lignocellulosic biomass into renewable energy sources, offering a sustainable alternative to fossil fuels. Similarly, in the production of fine chemicals and pharmaceuticals, enzyme-mediated synthesis enables precise control over reaction pathways, facilitating the production of complex molecules with unprecedented

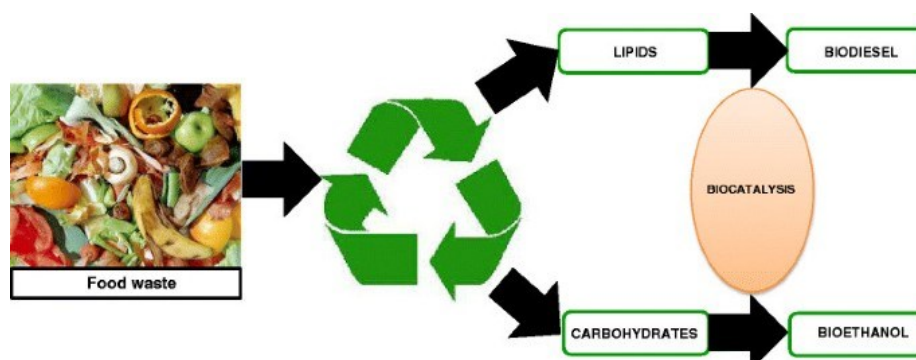
efficiency.

### 2.3 Metabolic Engineering and Genome Editing

Metabolic engineering involves the manipulation of metabolic pathways in microorganisms to enhance the production of desired compounds. Genome editing technologies, such as CRISPR-Cas9, enable precise modifications of microbial genomes, facilitating the development of microbial cell factories with improved productivity and sustainability [6]. The significance of metabolic engineering within industrial biotechnology lies in its ability to tailor microbial hosts for specific industrial applications. By rewiring metabolic pathways and optimizing enzyme expression levels, researchers can steer microbial metabolism towards the synthesis of target compounds with unprecedented efficiency. This fine-tuning of cellular machinery enables the production of a diverse array of valuable products, ranging from biofuels and pharmaceuticals to specialty chemicals and biopolymers. Genome editing technologies, such as CRISPR-Cas9, revolutionize the landscape of metabolic engineering, offering unprecedented precision and efficiency in genome manipulation. CRISPR-Cas9 serves as a molecular scalpel, enabling targeted modifications of microbial genomes with unparalleled accuracy. Whether it be gene knockouts, insertions, or modifications, CRISPR-Cas9 empowers researchers to sculpt microbial genomes with surgical precision, laying the foundation for the development of robust and efficient microbial cell factories. The applications of metabolic engineering and genome editing technologies extend across a myriad of industrial sectors, each benefiting from the transformative potential of tailored microbial hosts. In the realm of biofuel production, metabolic engineering enables the optimization of microbial strains for enhanced substrate utilization and product yield, paving the way for sustainable alternatives to fossil fuels. Similarly, in the production of high-value chemicals and pharmaceuticals, metabolic engineering facilitates the synthesis of complex molecules with precise control over product quality and purity.

### 2.4 Biosensors and Monitoring Technologies

Biosensors are analytical devices that detect biological molecules and monitor biochemical processes in real time. In industrial biotechnology, biosensors play a critical role in process monitoring and control, enabling the optimization of production processes and the detection of metabolic imbalances [7]. The schematic diagram of food waste recycling into biodiesel and bioethanol can be seen in Figure 2. The pivotal role of biosensors within industrial biotechnology cannot be overstated. These miniature marvels, with their unparalleled sensitivity and specificity, offer real-time insights into the intricate dance of biomolecular interactions occurring within microbial cell factories.



**Figure 2.** Recycling of food waste into biodiesel and bioethanol [7].

By continuously monitoring key process parameters such as substrate utilization rates, product formation kinetics, and metabolic fluxes, biosensors empower operators to optimize production processes with surgical precision, maximizing yield and efficiency while minimizing resource consumption. In the realm of biofuel production, biosensors serve as beacons of efficiency, guiding the optimization of fermentation processes and ensuring the judicious utilization of renewable feedstocks. By monitoring the levels of key metabolites and byproducts in real time, biosensors enable operators to fine-tune fermentation conditions, balancing nutrient availability, pH, and temperature to maximize biofuel yield and quality.

### **3. Sustainability and Environmental Impact of Industrial Biotechnology**

Industrial biotechnology offers significant potential to promote sustainability and mitigate environmental impacts associated with traditional manufacturing processes.

#### *3.1 Concept of Sustainable Manufacturing and Production*

Sustainable manufacturing and production involve the integration of environmental, social, and economic considerations into the design and operation of industrial processes. Industrial biotechnology offers a pathway towards sustainability by reducing dependence on fossil resources, minimizing waste generation, and lowering carbon emissions [8]. Sustainable manufacturing and production embody a fundamental shift in mindset, where the pursuit of profit converges with the imperative of environmental conservation and social equity. By prioritizing resource efficiency, waste reduction, and carbon neutrality, sustainable manufacturing seeks to minimize the ecological footprint of industrial activities while maximizing societal benefits. Industrial biotechnology stands as a linchpin in this endeavor, offering a suite of tools and technologies that enable the transition towards more sustainable practices. By reducing dependence on finite fossil resources and harnessing the power of renewable biomass feedstocks, industrial biotechnology mitigates the environmental impact of industrial processes while ensuring a secure and resilient supply chain.

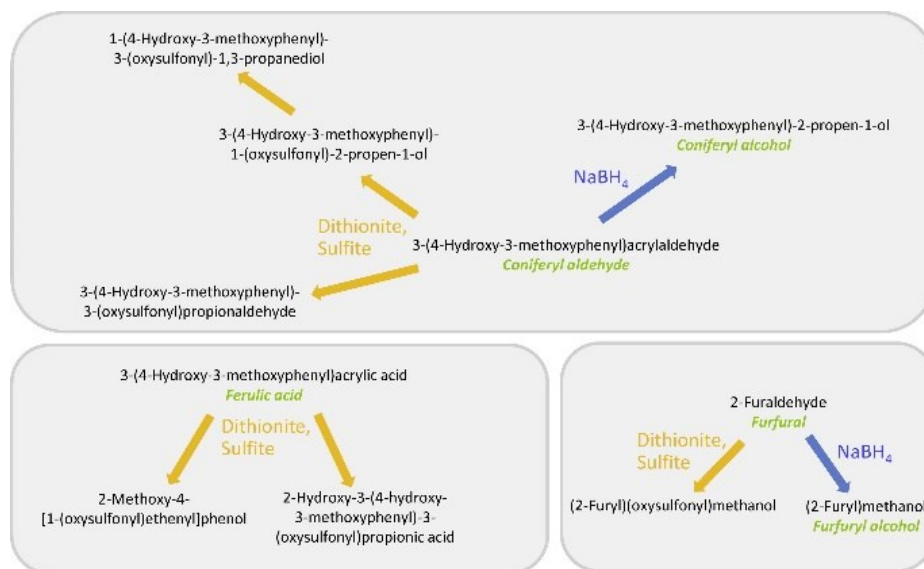
#### *3.2 Role of Industrial Biotechnology in Carbon Emission Reduction and Resource Utilization*

By utilizing renewable feedstocks such as biomass and waste streams, industrial biotechnology can reduce greenhouse gas emissions and mitigate climate change. Additionally, biorefinery concepts enable the efficient utilization of biomass resources, converting them into a range of bio-based products, including fuels, chemicals, and materials [9], see Figure 3. By embracing renewable feedstocks, industrial biotechnology offers a pathway towards carbon emission reduction and climate resilience. Unlike finite fossil resources, biomass and waste streams represent renewable and abundant sources of carbon that can be utilized without exacerbating climate change. Through processes such as fermentation, enzymatic conversion, and microbial biotransformation, industrial biotechnology transforms these carbon-rich feedstocks into biofuels, bioplastics, and other bio-based products, displacing their fossil-derived counterparts and reducing overall greenhouse gas emissions.

#### *3.3 Environmental Benefits and Ecosystem Services of Industrial Biotechnology*

Industrial biotechnology can contribute to environmental conservation by reducing the environmental footprint of industrial processes and promoting ecosystem services. For example, bio-based products derived from sustainable sources often have lower environmental impacts compared to their petroleum-based counterparts [10]. By prioritizing renewable feedstocks and innovative bioprocessing techniques, industrial biotechnology offers a pathway towards reducing the environmental footprint of industrial processes. Unlike their petroleum-based counterparts, bio-

based products derived from sustainable sources boast lower carbon emissions and reduced resource depletion, thereby mitigating greenhouse gas emissions and conserving natural resources. Moreover, industrial biotechnology fosters the development of bio-based products that promote ecosystem services and biodiversity conservation. From biodegradable plastics to bio-based chemicals, these products offer sustainable alternatives to conventional materials, reducing pollution and minimizing habitat destruction. By preserving natural ecosystems and reducing the demand for non-renewable resources, industrial biotechnology helps safeguard the ecological balance upon which all life depends.



**Figure 3.** Comparison of reactions effected by treatment of inhibitors with sulfur oxyanions (sulfite, dithionite) and sodium borohydride [10].

### 3.4 Challenges and Opportunities in Sustainable Development with Industrial Biotechnology

While industrial biotechnology holds great promise for sustainable manufacturing and production, several challenges must be addressed to realize its full potential. These include technological barriers, regulatory constraints, and market acceptance. However, ongoing research and innovation offer opportunities to overcome these challenges and advance the transition towards a more sustainable bioeconomy [11]. Technological barriers pose one of the primary challenges in the widespread adoption of industrial biotechnology. From optimizing bioprocessing techniques to engineering more efficient microbial strains, the road to sustainable industrial practices is paved with technical challenges that require innovative solutions. However, ongoing research and development efforts hold the promise of breakthroughs that will unlock new frontiers of possibility, propelling industrial biotechnology towards greater efficiency and effectiveness. Regulatory constraints also present a significant hurdle in the path towards sustainable development with industrial biotechnology. The complex regulatory landscape governing the production and use of bio-based products requires navigating a labyrinth of policies, standards, and certifications. However, by fostering dialogue and collaboration between industry stakeholders, policymakers, and regulatory agencies, opportunities arise to streamline regulatory processes and create a more conducive environment for innovation and investment.

## 4. Industrial Biotechnology in Food and Agriculture

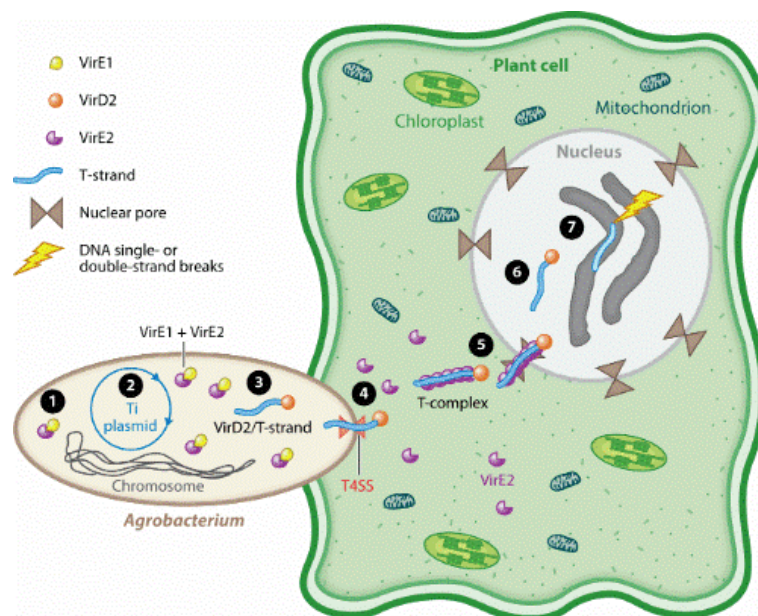
Industrial biotechnology plays a pivotal role in revolutionizing the food and agriculture sectors,



contributing to sustainable practices and improved food security.

#### 4.1 Biotechnological Innovations in Crop Improvement

Advancements in industrial biotechnology have facilitated the development of genetically modified crops with enhanced traits such as resistance to pests and diseases, tolerance to environmental stresses, and improved nutritional content. Genetic engineering techniques allow for precise manipulation of crop genomes to introduce beneficial traits, resulting in increased crop yields and reduced dependency on chemical inputs [12]. At the forefront of these innovations are genetically modified crops boasting enhanced traits tailored to address key agricultural concerns. Through precise manipulation of crop genomes, researchers can introduce beneficial traits such as resistance to pests and diseases, tolerance to environmental stresses, and improved nutritional content. By leveraging genetic engineering techniques, such as gene editing and transgenic manipulation, scientists can pinpoint and modify specific genes responsible for desired traits, resulting in crops with enhanced resilience and productivity. Resistance to pests and diseases stands as a hallmark achievement of biotechnological crop improvement. By introducing genes encoding insecticidal proteins or conferring resistance to viral and bacterial pathogens, genetically modified crops are fortified against common agricultural pests and diseases, reducing yield losses and minimizing the need for chemical pesticides. The agrobacterium-mediated plant transformation process is illustrated in Figure 4. Moreover, tolerance to environmental stresses, such as drought, salinity, and extreme temperatures, equips crops with the resilience needed to thrive in challenging growing conditions, ensuring stable yields and mitigating the impact of climate change.



**Figure 4.** Simplified model of the Agrobacterium-mediated plant transformation process emphasizing T-DNA integration and stable transgene expression [12].

#### 4.2 Biological Pest Control and Disease Management

Industrial biotechnology offers sustainable solutions for pest and disease management in agriculture through the development and application of biological control agents. Microbial biopesticides, such as *Bacillus thuringiensis* (Bt) and certain fungal species, provide effective alternatives to chemical pesticides, minimizing environmental contamination and preserving beneficial organisms in agroecosystems [13]. Bt, a naturally occurring bacterium, produces

insecticidal proteins that selectively target specific groups of pests, such as caterpillars and beetles, while posing minimal risk to non-target organisms and beneficial insects. By harnessing the genetic machinery of Bt and incorporating its insecticidal proteins into biopesticide formulations, researchers create potent tools for pest management that leave behind no harmful residues and pose no threat to human health or the environment. Biological pest control emerges as a cornerstone of sustainable agriculture, offering effective alternatives to chemical pesticides that minimize environmental contamination and preserve the delicate ecological balance of agricultural ecosystems.

#### *4.3 Bioprocessing in Food Production*

The use of industrial biotechnology in food processing and production enhances efficiency, safety, and nutritional quality. Enzymes derived from microbial sources are widely employed in food processing to catalyze specific reactions, improve texture, flavor, and shelf-life, and reduce the need for chemical additives. Moreover, fermentation technologies enable the production of various fermented foods and beverages, contributing to flavor development, preservation, and probiotic enrichment. Enzymes derived from microbial sources emerge as unsung heroes in the realm of food processing, catalyzing specific reactions that enhance texture, flavor, and shelf-life while reducing the reliance on chemical additives. These microbial enzymes, meticulously engineered through the principles of industrial biotechnology, offer precision and efficacy unmatched by their synthetic counterparts, ensuring the production of high-quality foods that meet consumer expectations for taste, texture, and safety. In food processing, microbial enzymes find applications across a diverse array of products, from dairy and baked goods to beverages and condiments. Amylases, proteases, and lipases, among others, play pivotal roles in starch hydrolysis, protein modification, and lipid breakdown, unlocking new dimensions of flavor and texture in foods while extending shelf-life and enhancing nutritional value. By harnessing the catalytic power of microbial enzymes, food manufacturers can achieve unprecedented levels of efficiency and consistency in their production processes, meeting the demands of a dynamic and evolving market landscape.

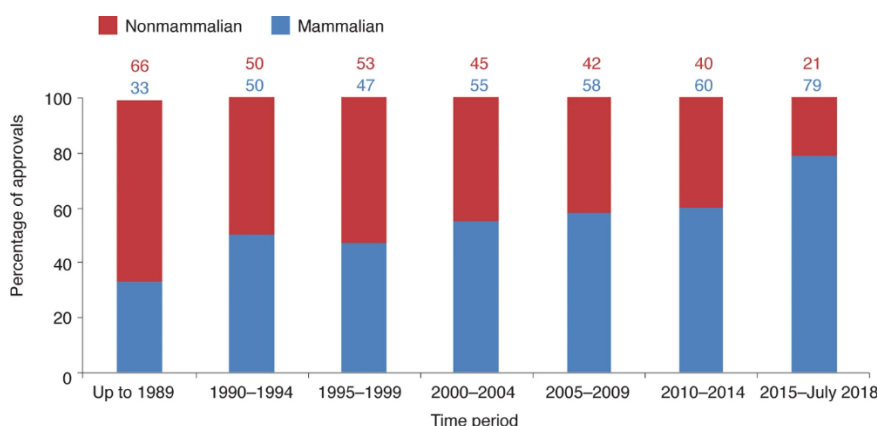
### **5. Industrial Biotechnology in Healthcare and Medicine**

#### *5.1 Biopharmaceutical Production*

Industrial biotechnology enables the large-scale production of biopharmaceuticals, including recombinant proteins, monoclonal antibodies, and therapeutic enzymes, through microbial or mammalian cell-based expression systems. Bioprocessing technologies ensure efficient production, purification, and formulation of biologics, expanding treatment options for various diseases and disorders [14]. The advent of industrial biotechnology marks a turning point in the production of biopharmaceuticals, offering a departure from traditional methods reliant on animal or human-derived sources. In the past few decades, the relative percentage of mammalian- versus nonmammalian-based production cell lines in the manufacture of biopharmaceuticals can be found in Figure 5. By leveraging microbial or mammalian cell-based expression systems, researchers can engineer host organisms to serve as efficient factories for the production of complex biologics with unparalleled precision and consistency. Recombinant proteins, monoclonal antibodies, and therapeutic enzymes, once limited by the constraints of natural sources, now become accessible on a commercial scale, paving the way for innovative therapies and personalized medicine. Central to the success of biopharmaceutical production is the development and refinement of bioprocessing technologies that enable the efficient cultivation, harvesting, and purification of biologics. Through the optimization of fermentation processes, downstream processing techniques, and formulation



strategies, researchers can streamline production workflows and maximize product yield, ensuring the cost-effective manufacture of biopharmaceuticals without compromising quality or safety.



**Figure 5.** Relative use of mammalian- versus nonmammalian-based production cell lines in the manufacture of biopharmaceuticals approved over the indicated periods [14].

### 5.2 Gene Therapy and Genome Editing

Advances in genome editing technologies, such as CRISPR-Cas9, have revolutionized gene therapy approaches, allowing for precise modification of genetic material to treat inherited disorders, genetic cancers, and infectious diseases. Industrial biotechnology facilitates the development of viral vectors, gene delivery systems, and gene editing tools for targeted and efficient gene therapy applications [15]. The advent of genome editing technologies, particularly CRISPR-Cas9, marks a watershed moment in the field of gene therapy, offering a powerful toolkit for the precise manipulation of genetic material to correct or mitigate disease-causing mutations. By harnessing the programmable nature of CRISPR-Cas9, researchers can target specific genes with surgical precision, enabling the correction of inherited disorders at the genetic level and offering hope to patients previously deemed untreatable. Moreover, the versatility of CRISPR-Cas9 extends beyond genetic correction to include gene knockouts, insertions, and modifications, providing a versatile platform for the development of novel therapeutic interventions. Central to the success of gene therapy applications is the development of viral vectors and gene delivery systems that facilitate the efficient and targeted delivery of therapeutic genes to diseased tissues or cells. Industrial biotechnology plays a pivotal role in this endeavor, leveraging recombinant DNA technologies and bioprocessing methodologies to engineer viral vectors and nanoparticles capable of safely and effectively transporting therapeutic cargo to its intended destination. From adeno-associated viruses (AAVs) to lentiviral vectors and lipid nanoparticles, these delivery vehicles serve as Trojan horses, ferrying therapeutic genes into target cells and tissues with precision and efficiency.

### 5.3 Point-of-Care Diagnostic

Industrial biotechnology contributes to the development of rapid, sensitive, and cost-effective diagnostic technologies for disease detection and monitoring. Innovations in molecular diagnostics, biosensors, and microfluidic devices enable point-of-care testing, improving healthcare accessibility and facilitating early diagnosis and treatment of diseases [16]. Industrial biotechnology plays a pivotal role in the development of point-of-care diagnostic technologies, leveraging its expertise in molecular biology, biochemistry, and engineering to create innovative solutions that empower patients and healthcare providers alike. At the forefront of this revolution are molecular diagnostics, which enable the rapid detection and characterization of pathogens, genetic mutations, and

biomarkers associated with disease. By harnessing the power of nucleic acid amplification techniques, such as polymerase chain reaction (PCR) and loop-mediated isothermal amplification (LAMP), molecular diagnostics offer unparalleled sensitivity and specificity in disease detection, allowing for timely intervention and treatment.

## 6. Conclusion

Industrial biotechnology has emerged as a potent force in advancing sustainable manufacturing and production across diverse sectors. By integrating biological principles with cutting-edge technologies, it offers innovative solutions to global challenges like environmental degradation, resource depletion, and public health crises.

This review comprehensively explores the fundamental principles and evolutionary journey of industrial biotechnology, from ancient fermentation practices to modern genetic manipulation and bioprocessing methodologies. It highlights the myriad applications of industrial biotechnology across pharmaceuticals, agriculture, energy, and healthcare, emphasizing its transformative impact on sustainable development. Key technologies such as microbial fermentation, enzyme engineering, metabolic engineering, and biosensors are examined in detail for their role in efficiently converting renewable feedstocks into bio-based products, optimizing enzyme properties, and developing microbial cell factories with enhanced productivity and sustainability.

Moreover, the review presents how industrial biotechnology promotes sustainability by reducing dependence on fossil resources, minimizing waste generation, and lowering carbon emissions. It identifies challenges and opportunities in sustainable development, stressing the importance of ongoing research, innovation, and collaboration. The application of industrial biotechnology in food and agriculture is summarized, highlighting its contributions to crop improvement, biological pest control, and food production processes. In healthcare and medicine, industrial biotechnology drives innovation in biopharmaceutical production, gene therapy, genome editing, and diagnostics, leading to improved healthcare outcomes and public health.

In conclusion, industrial biotechnology offers immense promise in addressing complex societal challenges. By harnessing nature's power and leveraging biotechnological innovations, we can create a more sustainable and resilient future for generations to come.

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