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Harnessing Microbial Enzymes for Sustainable Industries and Circular Bioeconomy

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Abstract
High-performing microbial enzymes are now fundamental to modern industrial biotechnology and dominate over 90 % of the commercial enzyme market worldwide. These enzymes are biologically categorised into oxidoreductases, transferases, hydrolases, lyases, isomerases, and ligases and are produced using optimized fermentation and downstream processing methods, primarily from bacteria, fungi, yeasts, and actinomycetes. They can be applied in many industries including food and beverages, pharmaceuticals, detergents, textiles, biofuels and remediation of the environment as they provide environmentally friendly solutions to traditional chemical processes. Although the production costs and stability of the enzymes are still an issue, the development of genetic engineering, protein design, and other new technologies such as AI and synthetic biology are promising steps to improve their performance and commercial feasibility. This review highlights how microbial enzyme technology can be used in innovation and sustainability in industries, which is consistent with green chemistry and the circular bioeconomy.

Keywords: Microbial Enzymes, Industrial Biotechnology, Enzyme Classification, Fermentation, Biocatalysis, Sustainable Applications.

1. Introduction
Enzymes are biological catalysts which increase the speed of biological reactions without being used up, are vital both to metabolism and the majority of biological functions [1]. In industrial biotechnology, these proteins are mostly derived from microorganisms. Microorganisms are the most preferable source of commercial uses because of their high growth rates, ease of genetic manipulation, low cost of cultivation, and capability of producing a large quantity of enzymes. Microbial enzymes control industry with more than 90 % of the world's commercial enzyme market. The most common sources of microbes used are Bacillus, Aspergillus, Penicillium, Trichoderma and Streptomyces [2].
This enzyme has been popular in food and beverages, pharmaceutical, textiles, detergent, paper and pulp, leather processing, bioenergy, and environmental biotechnology over the past decades and has led to innovation and efficiency. The need to have environmentally friendly and sustainable industry processes has necessitated the incorporation of microbial enzymes which are cleaner and more specific than the chemical catalysts [3]. The modern biotechnology depends on microbial enzymes, which are in line with the greener ideals of industrial practices. Therefore, their efficient manufacturing strategies, uses, and prospects make them socially relevant [4].

2. Sources of Microbial Enzymes
2.1 Bacteria
Due to their rapid growth in controlled cultivation, bacteria produce most industrial enzymes. Many bacteria produce enzymes [5]. For harsh industrial processing, many bacterial enzymes are robust, thermostable, and functional across a wide pH spectrum.
2.2 Fungi
Filamentous fungi like Aspergillus, Penicillium, Rhizopus, and Trichoderma produce most

extracellular enzymes for industrial use. Fungal enzymes like cellulases, pectinases, xylanases, and proteases are used in food processing, brewing, baking, and pharmaceuticals [6].

2.3 Yeasts

The enzymes of *Saccharomyces cerevisiae* and Candida species have wide industrial applications [7]. These Generally Recognized As Safe (GRAS) enzymes, which are essential to fermentation and food manufacturing, are widely used in baking, brewing, and bioethanol production.

3. Classification of Microbial Enzymes

3.1 Oxidoreductases

Oxidoreductases transfer electrons between molecules during oxidation-reduction reactions [8]. Biosensors for analyte detection, diagnostic assays in biochemical analysis, and bioremediation for degrading environmental pollutants use these enzymes due to their specificity and catalytic efficiency.

3.2 Transferases

Transferases are a major class of enzymes that transfer methyl, amino, or phosphate groups from donor to acceptor molecules [9]. In pharmaceutical synthesis, transaminases transfer amino groups and kinases transfer phosphate groups in biosynthetic pathways and drug precursor modification.

3.3 Hydrolases

Chemical bond hydrolases are the largest and most important enzyme group [10]. Amylases, proteases, lipases, cellulases, and pectinases dominate the detergent, food, and textile industries, breaking down starches, proteins, fats, cellulose, and pectic compounds.

4. Production of Microbial Enzymes

4.1 Strain Selection and Improvement

For enzyme production, a high-yielding microbial strain must be selected using random mutagenesis, adaptive evolution, or recombinant DNA technology [11].

4.2 Fermentation Techniques

Submerged Fermentation (SmF) and Solid-State Fermentation (SSF) produce most microbial enzymes. SmF is widely used in industry due to its ease of process control. SSF uses agricultural residues as solid substrates to produce fungal enzymes at a lower cost [12].

4.3 Downstream Processing

By filtration and centrifugation, microbial cells and debris are eliminated. Enzyme fractions are concentrated by precipitation followed by the separation of enzymes by size, charge or affinity by chromatography [13]. Enzymes may be purified to be used as lyophilized enzymes, on solid support, or to be used as a stable liquid.

5. Industrial Applications of Microbial Enzymes

5.1 Food and Beverage Industry

The microbial enzymes are applied in baking, brewing, dairy processing and in the process of clarifying the juice. The starch and gluten proteins are modified by microbial amylases and proteases to enhance the quality of dough and bread [14]. Microbial enzymes enhance the efficiency, quality and specificity of processing foods since they are widely used.

5.2 Detergent Industry

Modern laundry detergents include proteases, lipases, and amylases to eliminate various stains. Proteins stains such as blood, egg and grass are decomposed by proteins enzymes into soluble peptides and amino acid in water [15]. Lipases decompose the oil and fat triglycerides to glycerol and free fatty acids.

5.3 Textile and Leather Industry

Enzymatic processing replaces the use of harsh chemicals in the process by using renewable chemicals, making the textile production to be more sustainable [16]. Amylases do not destroy cellulose fibres and eliminate starch-based sizing agents. Biocatalytic technologies at low temperatures and pH processes, consume less energy, and yield lower environmental impacts than chemical technologies in textile production.

5.4 Biofuel Production

Lignocellulosic biomass polysaccharides can be transformed into monomeric sugars as a result of biorefining with the help of cellulases and hemicelluloses. The glucose and xylose are fermented by microbes to produce bioethanol [17]. Therefore, in most cases physiochemical pretreatment is necessary to break this matrix and increase substrate porosity and enzymatic absorption.

6. Recent Advances in Microbial Enzyme Technology

New biocatalysts that have been identified and engineered with genomic and metagenomics technologies have enhanced enzyme productivity, stability, and specificity. Extremozymes of extremophilic bacteria are commercially used in extreme temperatures, pH, and salinity [18]. Protein engineering and enzyme immobilization facilitate the design of enzymes and stability concerning heterogeneous systems in the optimal way.

7. Challenges and Limitations

Several factors limit the widespread commercial application of microbial enzymes. Complex fermentation and downstream purification requirements increase production costs, which pose a threat to the economic sustainability of large-scale systems. Some of the native enzymes are inherently labile, such as denaturation at non-ambient temperatures or at pH extremes and susceptibility to bioreactor conditions [19]. Protein design and directed evolution enhances enzyme stability, catalytic process, and expression outcomes with the use of genetic engineering. Process engineering is undertaken to enhance stability of the reactor through optimization of fermentation process, downstream operations and immobilization processes.

8. Future Prospects

Microbial enzymes are preferred due to the growing demand for green industrial technologies. Chemical processes used in bioremediation, biofuel production, medicine and consumer goods can be substituted with biocatalysts that can produce processes that are more efficient and eco-friendlier. The principles of green chemistry for its specificity, biodegradability, and mild operation are essential for a circular bioeconomy [20]. Enzyme development will be transformed by advances in AI, synthetic biology, and systems biology. Machine learning and Artificial Intelligence will be used in silico and drug discovery to predict new enzyme functions and structures, based on genetic databases. Systems biology uses the knowledge of microbial physiology to optimize production hosts and metabolic pathways and synthetic biology to heterologous express enzymes.

9. Conclusion
Microbial enzymes are critical in industrial biotechnology today, offering efficient, specific, and sustainable catalyst solutions in the food and beverage, pharmaceutical, detergents, textile, biofuel production, and environmental remediation. Although manufacturing costs and enzyme stability remain challenges, genetic engineering, protein design, and new technologies such as AI and synthetic biology will enhance performance and sustainability. Microbial enzymes will create new innovations, suit green chemistry principles, and be used to shift to a circular bioeconomy because the global needs of processes that are eco-friendly will increase their essential in a greener industrial future generation.

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