International Journal of Enhanced Research in Science, Technology & Engineering
ISSN: 2319-7463, Vol. 12 Issue 6, June-2023, Impact Factor: 7.957

"Exploring the Diverse Applications of Industrial Enzymes: Catalysts for Sustainable Industrial Processes"

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ABSTRACT

Industrial enzymes are specialised proteins used in a variety of industrial processes owing to their capacity to catalyse particular chemical reactions. These enzymes, which are produced by microbial fermentation or genetically modified organisms, have a number of benefits over conventional chemical catalysts, including more selectivity, milder reaction conditions, and better sustainability. Due to their exceptional catalytic efficiency and specificity, enzymes serve as biocatalysts and are essential in many industrial applications. Enzymes are frequently used in the food and beverage industries, where they help turn basic ingredients like carbohydrates, proteins, and lipids into tasty finished goods. Additionally, the textile sector uses enzymes for procedures like desizing, bio-polishing, and denim fading to enhance fabric quality and minimise environmental impact. Enzymes play a crucial role in laundry detergents in the detergent business, providing efficient stain removal and energy efficiency. Enzymes are used in medication synthesis by the pharmaceutical industry, resulting in more productive production methods and a smaller environmental impact. Enzymes are also essential for producing biofuels, notably the enzymatic hydrolysis of biomass to produce bioethanol. Finally, enzymes are used in waste management to help treat and degrade a variety of contaminants. Enzymes provide a viable and effective replacement for conventional chemical processes in many industrial sectors, encouraging environmentally friendly practices and raising product quality.

Key Words: Industrial Enzymes, Catalysis, Biofuels, Fermentation, Sustainable

INTRODUCTION

Biocatalysts that are commonly employed in many areas of industrial production are industrial enzymes. In comparison to conventional chemical processes, these specialised proteins promote and speed up chemical reactions. Industrial enzymes have drawn a lot of interest because of their adaptability, focus, and environmental friendliness.

Enzymes have been used in industrial operations since ancient times when they were used in things like brewing, cheese-making, and bread-making. The industrial enzyme business has undergone a revolution, though, because of developments in contemporary biotechnology, which have made it possible to produce enzymes on a massive scale and broaden their applications.

The ability of industrial enzymes to operate in benign operating conditions, such as moderate temperatures and pH ranges, minimises energy consumption and has a positive impact on the environment. Furthermore, enzymes have excellent substrate and reaction specificity, which increases efficiency and decreases waste production.

The enzyme industry has undergone rapid development primarily in the past four decades, driven by advancements in modern biotechnology [1]. Enzymes have been utilized since ancient times in the production of various food products, including cheese, sourdough, beer, wine, and vinegar, as well as in the manufacturing of commodities such as leather, indigo, and linen [2][3]. In those early processes, enzymes were derived from spontaneously growing microorganisms or added preparations like calves' rumen or papaya fruit, without being purified or well-characterized [3].

However, the development of fermentation processes in the later part of the last century revolutionized the production of enzymes by using selected production strains, enabling large-scale manufacturing of purified and well-characterized enzyme preparations [4]. This breakthrough facilitated the integration of enzymes into true industrial products and processes, including the detergent, textile, and starch industries [3]. Additionally, the application of recombinant gene technology further improved manufacturing processes and made the commercialization of previously inaccessible enzymes possible [4].

Furthermore, recent advancements in modern biotechnology, such as protein engineering and directed evolution, have significantly transformed the development of industrial enzymes [3]. These innovations have facilitated the production of tailor-made enzymes with new activities and adapted characteristics for diverse process conditions, leading to further expansion of their industrial applications [4]. As a result, the enzyme industry has become highly diversified and continues to grow in terms of size and complexity [3].

The majority of industrial enzymes in use today have a hydrolytic function and are used to break down a variety of natural compounds. Due to their extensive use in the dairy and detergent sectors, proteases in particular continue to be the most common enzyme class. Amylases and cellulases, the second-largest group of carbohydrases, are used in the starch, textile, detergent, and baking industries [1].

Industrial enzymes now have a $1.5 billion market value worldwide, up from $1 billion in 1995 [5]. However, in certain important technical industries, including the detergent industry, growth has been static [5].

The baking and animal feed industries have experienced the fastest growth in the past decade, while other industries, ranging from organic synthesis to paper and pulp and personal care, have also contributed to the overall expansion of the enzyme market [1].

Recombinant DNA technologies, protein engineering, and developments in fermentation methods have all aided in the development of industrial enzymes. Enzyme manufacturing on a wide scale is made possible by fermentation procedures that make use of particular microbes or genetically modified organisms. Through the use of recombinant DNA technology, desirable genes can be introduced into host species, enabling the creation of enzymes that were previously scarce. Enzymes can be altered and optimised using protein engineering techniques to improve their functionality, stability, and specificity for different industrial applications [6].

Industrial enzymes are becoming more and more valued resources for attaining these aims as the need for sustainable and ecologically friendly processes rises. They provide substantial advantages like decreased energy use, reduced waste production, and increased process effectiveness. The field of industrial enzymes is anticipated to grow further with continued study and technical development, resulting in the creation of novel enzymes and the investigation of innovative uses in a variety of industries.In addition to enhancing process economics, their utilisation promotes environmental sustainability[6].

This review will examine the most recent improvements in the technical uses of enzymes, segment by segment, highlighting the important developments that have facilitated these uses.

Enzymes in Detergent Industry

The detergent industry, which represents the largest utilisation in terms of volume and value [7], continues to be at the forefront of industrial enzyme uses. Proteases are the most common enzymes utilised, although other hydrolases with unique features are often added to offer a variety of advantages, including the elimination of specific stains [8]. Proteases and amylases are examples of conventional detergent enzymes that have undergone improvements as a result of ongoing biotechnological developments. These enzymes from the second and third generations have undergone extensive optimisation to satisfy the changing performance standards for detergents, whose composition is continually being improved [9].

The compatibility of enzymes with detergent components, notably their stability features, is one of the major factors to be taken into account while developing detergent enzymes. Additionally, recent work has concentrated on improving the enzymes' effectiveness at lower temperatures, which is in line with the development of less energy-intensive laundry and dishwashing practises [10]. When it comes to overcoming the difficulties of effective cleaning and stain removal at lower temperatures, enzyme technology is essential.

Novel amylases that have been engineered to display increased activity at lower temperatures and alkaline pH, while preserving stability under detergent conditions, are notable examples of second-generation detergent enzymes. These enzymes are created using a combination of rational protein engineering techniques and microbial screening [11]. Proteases that can operate at low temperatures have been found in nature, and additional advancements have been made via techniques of lab-directed evolution [12]. Scientists have isolated new proteases from a pool of 26 subtilisin proteases via DNA shuffling, producing enzymes with improved activity and stability at alkaline pH—important properties for detergent proteases [13].

An important development in detergent enzymes in recent years has been the appearance of a new enzyme class, notably mannanases. Procter & Gamble and Novozymes worked together to develop this innovation [14]. The collaboration between Procter & Gamble and Novozymes to create mannanases is a prime example of the detergent enzymes' ongoing innovation and advancement. Manufacturers can improve the effectiveness and efficiency of stain removal by broadening the variety of enzymes used in detergents. This advancement is essential because it tackles unique difficulties in erasing guar gum stains, which can be extremely difficult.

Procter & Gamble and Novozymes' partnership demonstrates the industry's dedication to expanding enzyme technology and developing cutting-edge cleaning and stain removal methods. The detergent business may offer consumers cleaners that are more effective and efficient by consistently researching and launching new enzyme classes, such mannanases.

Guar gum, a typical stabiliser and thickening component in food items, plays a significant role in the efficient removal of numerous food stains.Guar gum, a stabiliser and thickening substance frequently used in food items, is recognised for helping to remove various food stains effectively. The detergent sector has been actively working to improve enzyme activity, stability, and compatibility with detergent formulations since they understand how important it is to deal with these stains. The breakthroughs in industrial enzymes have been fueled by this continual research and development in the detergent sector.

The detergent business improves enzyme activity, stability, and compatibility to offer more potent stain removal and cleaning capabilities. This is especially true now that energy-saving techniques are increasingly emphasized in home and commercial cleaning methods.In order to satisfy changing consumer needs, the detergent industry must make improvements to enzyme activity and compatibility with detergent formulations. These advancements help remove stains more successfully and offer energy savings by lowering the temperature requirements for cleaning procedures.With a continuing focus on enhancing enzyme activity, stability, and compatibility with detergent formulations, the detergent industry remains the primary force behind the research and use of industrial enzymes. These developments pave the way for more effective stain removal and cleaning, which helps domestic and commercial cleaning procedures save energy.

Enzymes in Fuel Production

Based on the primary ingredients and production methods, biofuels are divided into generations. Bio-alcohols like ethanol, butanol, and propanol are produced as a by-product of the fermentation process used to produce first-generation biofuels from sugar and starch-producing plants. Cellulose from non-food crops and leftover biomass is used to make cellulosic biofuels, which are a type of second-generation biofuel. Algal/microalgae species are used to create third-generation biofuels, which have high energy efficiency and provide benefits for the economy, society, and environment for both domestic and industrial use [15][16].

Municipal garbage, agricultural residues, industrial organic waste, and livestock waste are all examples of waste biomass that can make good sources for biofuel production and help to create a low-carbon environment and a circular economy that is sustainable [17][18]. For instance, the creation of biochar from orange peels effectively makes use of waste biomass [18].

Various characteristics, including water content, volatile components, ash content, net calorific value, and chemical composition, influence the choice of suitable waste biomass for biofuel generation [19][20]. In comparison to rice waste and date fruit waste, studies have indicated that Jatropha fruit waste (cake) demonstrates the superior potential for the manufacture of biofuels [20].

In the process of producing biofuel, enzymes provide benefits like process effectiveness, cost-effectiveness, and environmental friendliness. Microbial-driven enzymes are frequently employed, highlighting the significance of a thorough understanding of microorganisms and their particular enzymes for various biofuels [21]. Enzyme-based biofuel cells (EBCs), which focus on using glucose as a biofuel to generate power through the use of different nanomaterials, are a recent discovery [22].With the development and improvement of cost-effective bioprocesses, the generation of biohydrogen, biodiesel, biogas, and bioethanol would be an ideal option to replace the energy of fossil fuels. Along with having a thorough understanding of its process and the microorganisms from which these enzymes are derived, it is crucial to place emphasis on the enzymes involved in the generation of various biofuels. Enzymes that work well and efficiently will help the economy's transition to a biofuels-based one. As engineering techniques and synthetic biology have advanced, many microbe strains have been employed to increase the production of sustainable enzymes for biofuels.

Enzymes in the Production of Textiles

Despite having a large impact on the world economy, the manufacture of textiles frequently has negative environmental effects. Enzymes have become useful tools in the textile industry in recent years, providing effective and sustainable solutions to a variety of problems. One of the areas of industrial enzymology that is expanding the fastest is the use of enzymes in the textile industry. Amylases, catalase, and laccase are the enzymes that are utilised in the textile industry to remove starch, break down excess hydrogen peroxide, bleach fabrics, and break down lignin. Due to their non-toxic and environmentally friendly qualities, enzymes are being used more and more in the chemical processing of textiles as the need for textile manufacturers to prevent pollution in textile production becomes more and more significant. The most recent commercial advancements involve the use of cellulases for denim finishing and lactases for bleaching and decolorizing textile effluents. Because enzymes are highly specific, effective, and operate in benign settings, their employment in technology is appealing. Additionally, using enzymes speeds up processes, saves energy and water, improves product quality, and has the ability to integrate processes. The objective is to educate the textile technologist about enzymes and how to employ them with textiles.

Biocatalysts known as enzymes speed up chemical reactions. Enzymes have various benefits over conventional chemical processes for processing textiles, including less energy and water use, softer processing conditions, and better product quality. The textile industry uses enzymes at several stages [23].

Biocatalysts known as enzymes speed up chemical reactions. Enzymes have various benefits over conventional chemical processes for processing textiles, including less energy and water use, softer processing conditions, and better product quality. Enzymes are utilised in the desizing, scouring, bleaching, dying, and finishing stages of textile manufacture.

Desizing and scouring: While scouring eliminates impurities including waxes, pectins, and oils, desizing involves the removal of sizing agents from fabrics. Alpha-amylases and cellulases are employed for effective desizing and scouring, which enhances the absorbency, dye uptake, and general quality of the cloth. These enzymatic procedures are less harmful to the environment than conventional chemical ones.

Bleaching: Enzymes are essential to the bleaching process because they break down lignin, pectin, and other contaminants in the cloth. Utilising enzymes like xylanase and laccase, enzymatic bleaching lessens the need for harsh chemicals and high heat, reducing the impact on the environment and improving fabric brightness.

Dyeing and Colouring: Enzymes are used in several stages of textile dyeing, such as colour removal, denim fading, and enhancing colour fastness. The fabric surface can be better prepared for dye penetration using enzymatic techniques like bio-bleaching and bio-scouring, which can improve colour intensity and cut down on dye usage.

Finishing: Enzymes offer creative approaches to textile finishing, giving materials the desired practical qualities. For instance, soft, smooth, wrinkle-free finishes can be produced using enzymes like cellulases and lipases instead of harsh chemicals and mechanical treatments. The popularity of enzymatic finishing techniques has grown as a result of their sustainability, enhanced fabric feel, and low energy requirements.

Environmental Benefits: The textile industry uses enzymes to preserve the environment and promote sustainability. Low temperatures and quick processing durations are typical requirements for enzymatic reactions, which work under more tolerant circumstances. As a result, energy is saved, and carbon emissions are decreased. Enzymatic processes also minimise the ecological effect by using less water and releasing fewer dangerous chemicals into the environment.

Higher-quality finished goods are a result of desired fabric qualities acquired by enzymatic activities, such as greater fabric absorbency, increased dye uptake, improved colour fastness, and desirable fabric features. By increasing processing effectiveness and minimising the need for harsh chemicals and repetitive treatments, enzymes can also assist lower production costs.

The textile industry has undergone a revolution because to enzymes, which offer effective and environmentally friendly substitutes for conventional chemical procedures. Enzymes are used in textile processing for a variety of reasons, including decreased environmental impact, higher performance, and better fabric quality. An important step towards a greener and more sustainable future is the adoption of enzyme technology in the textile industry [24].

Enhancing Nutrient Utilisation and Environmental Sustainability with Enzymes in the Feed Industry

Enzymes have become significant feed additions in the cattle business, solving issues with sustainability and nutrient utilisation. In the feed industry's use of enzymes like xylanases, β-glucanases, and phytases is very well documented, with special emphasis on how they help animals better absorb nutrients and have a smaller negative impact on the environment.

Cereal-based feed with xylanases and beta-glucanases:
For monogastric animals, xylanases and beta-glucanases are added as feed additives to cereal-based diets. These enzymes aid in the breakdown of the complex carbohydrates found in plant-based feeds, improving nutritional availability and improving animal performance [25].

Phytases for Better Utilisation of Phosphorus:
Although phosphorus is an essential mineral for animal diets, it is frequently bound in phytic acid in feeds made from plants. Monogastric animals' low phosphorus utilisation results from a lack of the enzymes needed for effective phytic acid breakdown. Enzymes called phytoses, which break down phytic acid, have drawn a lot of interest as feed additives. Phytases increase animal phosphorus uptake by enhancing the release of phosphorus from phytic acid [26]. This is especially important since there are restrictions on conventional inorganic phosphorus sources, including bone meal, and because phosphorus excretion must be decreased to lessen environmental effect [27].

Research is now being done to improve the effectiveness of phytases in feed formulations. In order to increase phosphorus release, new fungal phytases with noticeably greater specific activity have been discovered [28]. To improve the catalytic activity of fungal phytases, methods including site-directed mutagenesis based on three-dimensional structural analyses have been used [29]. These developments are meant to maximise phytases' abilities to increase phosphorus utilisation in animal diets.

Feed enzymes, such as phytases, have been discovered to have indirect impacts on the intake of other nutrients in addition to their direct impact on phosphorus utilisation [30]. In order to better understand these impacts and create enzyme formulations that enhance nutrient utilisation and advance animal health, more research is now being conducted. Future prospects include the continuous development of enzyme technology, which will promote sustainable livestock production methods and allow for better nutrient utilisation in animal diets.By increasing nutrient utilisation and minimising environmental effect, enzymes are essential in the feed sector. In monogastric animals, the use of enzymes such xylanases, β-glucanases, and phytases improves the utilisation of phosphorus and the breakdown of complex polysaccharides. The optimisation of nutrient utilisation in animal diets has potential for supporting efficient and sustainable livestock production, according to ongoing research and developments in enzyme technology.

Enzymes for the Food Industry: Innovations and Various Uses
The use of enzymes in the food business has grown significantly, with uses ranging from texturizing to flavouring. This article examines the various uses of enzymes in the food-processing industry, highlighting current developments and their potential for further development in the future.

Using transglutaminase to Texture:
Through protein cross-linking, transglutaminase has become recognised as a useful texturizing agent in the food processing industry, enhancing the viscoelastic qualities of goods like sausages, noodles, and yoghurt [31]. Although ongoing attempts are being made to expand the availability of economically viable transglutaminase enzymes through recombinant synthesis, this problem still exists.

Lipolytic Enzymes in Baking: According to studies [32, 33], lipolytic enzymes are being used more and more in baking. Recent research suggests that phosphor-lipases can produce emulsifying lipids in situ by degrading polar wheat lipids in place of or in addition to conventional emulsifiers. Additionally, studies are concentrating on the causes of bread staling and the enzymatic prevention of staling employing xylanases and α-amylases [34]. Bread softness and elasticity are maintained in part by the starch and hemicellulose fractions' ability to retain and bind water.

Novel Applications: Although there is a dearth of literature on a number of promising new applications of enzymes in the food business. By catalysing the cross-linking of polyphenols, laccase enzymes have been employed to clarify juice by enabling their simple removal through filtration. By catalysing the cross-linking of polyphenols, laccase enzymes have been employed to clarify juice by enabling their simple removal through filtration. Additionally, laccases have been used to improve the flavour of beer. New uses in the food sector may be discovered by further investigation of various enzyme classes [35].

Enzymes have completely changed the way that food is produced, with uses ranging from flavouring to texturizing. Recent developments have demonstrated tremendous potential for enhancing product quality and processing effectiveness, including the use of transglutaminase for texturizing and lipolytic enzymes in baking. In addition, new uses for enzymes, such as laccase enzymes, show how widely used they are in the food sector. Enzyme technology will improve further with continued study and invention, resulting in better food processing.

Oil and Fat Processing

Several innovative enzyme-based techniques have recently been established in the fat and oil industries. Even though the technique of interesterifying triglycerides using immobilised lipases was first reported in the 1980s, it has not yet proven to be sufficiently cost-effective to be used in actual large-scale applications, such the manufacturing of margarine [36]. However, these issues have been resolved by improvements in enzyme synthesis and immobilisation methods.

Utilising granulated silica to immobilise lipases has greatly decreased process costs, which is a significant development [37]. This breakthrough has made it possible to produce commodity fats and oils free of trans fatty acids using enzyme-based techniques, which will result in healthier food items [37].

The "de-gumming" process, which eliminates phospholipids from vegetable oils, is another notable enzyme-based procedure. Highly selective microbial phospholipases are used in this procedure [38]. This enzymatic step can be added to save energy and water, which is good for the environment as well as the industry [38].

These enzyme-based procedures show how enzymes can improve sustainability and productivity in the fat and oil sectors. It is anticipated that ongoing research and development in enzyme technologies will spur additional improvements in these procedures and broaden their applications.

Enzymes for organic synthesis

Chemical synthesis depends on enzymes for organic synthesis, which have many advantages over conventional chemical processes. In contrast to other industries, the chemical industry has been rather sluggish to adopt enzyme catalysis despite its considerable promise. However, the manufacture of numerous compounds using enzyme-based techniques has seen tremendous growth and wide adoption recently, signalling a turning point in the industry [34].

The creation of single-enantiomer intermediates for use in the synthesis of medicines and agrochemicals is a well-known application of enzymes in organic synthesis. The required biological activity and safety of these chemicals depend on the selective production of particular enantiomers, which is only possible through enzymatic reactions. Due to the fact that only a few number of enzymes have broad applicability across several synthetic pathways, this market segment is highly fragmented.

Novel enzymatic processes have been created as a result of recent developments in enzyme-based catalysis. For instance, lipases are useful in the synthesis of enantiopure alcohols and amides. These enzymes have a high degree of selectivity and are effective at resolving chiral mixtures from racemic mixtures. While acylases have been used to create novel semi-synthetic penicillins, nitrilases have been used to produce enantiopure carboxylic acids [39].

It is significant to remember that many businesses are only just beginning to investigate and utilise the potential of enzyme-based catalysis in organic synthesis. This suggests that there is still a great deal of space for new research and breakthroughs in this area. Expanding the range of enzymes and improving their catalytic capabilities for certain chemical transformations are the goals of ongoing research in the fields of enzyme engineering, directed evolution, and protein design.

The use of enzyme-based techniques in organic synthesis has a number of benefits. Enzymes frequently operate with excellent selectivity and under benign reaction conditions, minimising the creation of undesirable byproducts and minimising waste. Enzyme catalysis can also increase overall process efficiency and allow the use of renewable starting materials. With predictions of continuous development and innovation in the upcoming years, these considerations help to explain the increased interest in and investment in enzyme-based organic synthesis.

CONCLUSION

Enzymes are now crucial in many industrial fields, and their uses are constantly growing. Enzymes are being created for processes that were previously thought to be improbable candidates for enzymatic catalysis thanks to breakthroughs in biotechnology. This development broadens the use of enzyme utilisation and creates new possibilities.

The capacity of enzymes to function as extremely effective catalysts under benign reaction circumstances is one of their main advantages. This trait results in enormous resource savings, including water and energy, which are advantageous to the economy and the environment. Such resource preservation is especially important in a world that is struggling with issues like population growth and resource depletion.Enzyme technology has a great deal of potential for solving problems that different sectors will confront in the future. It provides environmentally friendly substitutes for conventional chemical processes, lessening the impact on the environment and encouraging resource utilisation that is more effective. We can anticipate even bigger discoveries and innovative uses of enzymes in the years to come as study and development in protein design, biocatalysis, and enzyme engineering continue.The development of an industrial environment that is more resource- and sustainably efficient depends in large part on enzyme technology. Industries may help fulfill the demands of a changing world while reducing their ecological impact by utilising the power of enzymes. The potential of enzymes will be further realised by continued innovation and cooperation between academics, business, and biotechnology, which will be advantageous for society, the economy, and the environment.

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