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Review

Enzymes in the Removal of Harmful Substances: The Potential of Biotechnology in Environmental Protection

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Abstract: In the face of growing environmental pressures, enzymes are emerging as powerful and versatile tools for combating pollution. With their exceptional specificity, ability to function under mild conditions, and minimal environmental impact, enzymes offer a sustainable alternative to traditional remediation methods. They can effectively break down and neutralize a wide range of pollutants—including pesticides, pharmaceuticals, heavy metals, dyes, and microplastics—without generating toxic by-products. Innovations such as enzyme immobilization, microbial consortia, and hybrid technologies have significantly enhanced their stability and performance in real-world conditions. Advances in protein engineering and the use of artificial intelligence now enable the design of tailor-made enzymes with improved resilience and substrate range. Enzymes also play a vital role in the circular economy by transforming waste into valuable secondary raw materials, biofuels, and biodegradable products. While challenges remain in scaling up these technologies and reducing costs, the potential of enzyme-based biotechnologies is immense, positioning them as a promising path toward environmentally friendly and efficient solutions for pollution control, resource recovery, climate-resilient development, and as a cornerstone of future environmental strategies.

Keywords: enzymes; bioremediation; wastewater treatment; micropollutants; sustainable development

1. Introduction

Modern civilization faces many pollution challenges. Industry, agriculture, transportation and households emit many toxic compounds into the environment, such as pesticides, heavy metals, detergents, pharmaceuticals and plastics, including microplastics [1]. These pollutants have a negative impact on both the environment and human and animal health. Traditional methods of removing these substances, such as combustion, filtration, deposition or chemical neutralization, often prove to be costly, energy-intensive, and not entirely effective, as well as not environmentally friendly. Moreover, in many cases, the byproducts of these processes themselves can be a new source of pollution [2].

An alternative that has become increasingly important in recent decades is biotechnological methods of environmental cleanup based on the use of microorganisms and/or enzymes. Enzymes are biocatalysts that accelerate chemical reactions under mild thermal and pH conditions, making them more environmentally friendly than classical chemical methods. Their high selectivity, efficiency and ability to operate in complex mixtures of chemical and biological agents make them ideal candidates for applications in the removal of harmful substances. Key classes of enzymes with particular relevance to bioremediation include hydrolases, responsible for the degradation of complex organic molecules; oxidoreductases, which mediate redox transformations; transferases, facilitating the transfer of functional groups to enhance pollutant modification; and lyases, catalyzing the cleavage of chemical bonds without hydrolysis or oxidation [3].

In the face of intensifying climate change, increasing numbers of toxic substances in the environment, and waste management challenges, enzyme technologies can play a key role in the process of green transformation and building a more sustainable civilization. Against this backdrop, this study not only analyzes the current state of knowledge in the field of enzymatic environmental cleaning but also presents potential directions for further development of this technology. Importantly, it should also be emphasized that this article is a review paper. Its purpose is not to present new experimental results, but rather to synthesize and critically analyze existing knowledge in the field, highlighting both established applications and emerging perspectives of enzymatic technologies in environmental cleanup.

2. Use of Enzymes for Remediation of Pollutants

Enzymes, both crude and purified, can be used as free enzymes as well as immobilized enzymes for the removal of a wide range of contaminants, including pesticides and herbicides, pharmaceuticals, dyes, phenols, and liquid heavy metal ions [4]. Recently, more and more attention has also been paid to the enzymatic conversion of microplastics.

Pesticides and herbicides are chemical compounds commonly used in agriculture, horticulture and forestry to protect crops from weeds, pests and diseases. Although their use contributes to increased yields and agricultural efficiency, excessive and uncontrolled use leads to serious environmental consequences. These compounds can contaminate soils, ground and surface waters and the air, showing toxicity to non-target organisms and the ability to bioaccumulate in food chains [5].

Many pesticides are compounds that are difficult to biodegrade, resistant to natural degradation processes. In response to these threats, enzymatic bioremediation technology is developing, based on the use of biocatalysts capable of selectively degrading harmful substances. In the processes of enzymatic removal of pesticides and herbicides from the environment, various classes of enzymes play a special role, which, due to their catalytic specificity, are capable of efficiently detoxifying and degrading complex chemical compounds. These enzymes are often naturally produced by microorganisms, plants and even higher organisms, but their acquisition and modification are also possible through modern genetic engineering and biotechnology techniques [6].

The most important groups of enzymes involved in pesticide degradation primarily include hydrolases, oxidases, organophosphate hydrolases, haloalkane dehalogenases and peroxidases [7]. Hydrolases, such as esterases and amidases, catalyse the breakdown of ester and amide bonds in pesticide molecules, leading to less toxic products with increased polarity and susceptibility to further biological degradation [8]. Oxidases, including mono- and dioxygenases, on the other hand, play an important role in modifying aromatic structures by introducing oxygen atoms into them, facilitating their further enzymatic and chemical degradation [9]. These enzymes are particularly key in the neutralization of compounds such as chlorpyrifos, diazinon and atrazine.

Organophosphate hydrolases (OPHs), which catalyse the breakdown of phosphoester bonds in compounds such as parathion or chlorpyrifos, play a particular role in the biodegradation of organophosphorus pesticides [10]. The products of their action are much less toxic compounds that can be more easily broken down or inactivated in the environment. These enzymes are produced by various soil bacteria, including *Pseudomonas diminuta* and *Flavobacterium* sp. [11]. Another important group are haloalkane dehalogenases, which remove halogen atoms (mainly chlorine) from the molecules of chlorinated pesticides such as dichlorodiphenyltrichloroethane (DDT) or dichlorophenols [12]. This makes the chemical structure of these substances less stable and more susceptible to further biodegradation transformations. Equally important are peroxidases of plant and bacterial origin, which are involved in the oxidation of phenolic pesticides such as diuron, 2-methyl-4-chlorophenoxyacetic acid (MCPA) or 2,4-dichlorophenoxyacetic acid (2,4-D) [13]. Thanks to these properties, peroxidases have found applications in biological treatment systems for surface water, agricultural wastewater and soil contaminated with agrochemical residues, among others.

Another group of pollutants present in the environment are drugs and their metabolites, categorised as so-called endocrine disrupting chemicals (EDCs), increasingly detected in municipal wastewater, surface water and groundwater. This group includes antibiotics, hormones, painkillers, psychotropic drugs, antidepressants and cytostatic drugs, among others [14]. The presence of these substances in the environment, even in trace concentrations (ng/L to µg/L), can lead to a number of adverse effects including development of antibiotic resistance in environmental bacteria, endocrine disruption in aquatic organisms, bioaccumulation of these chemicals in the trophic chain and/or developmental and reproductive disorders in fish, amphibians and invertebrates [15]. Conventional wastewater treatment methods are not sufficiently effective in removing such micropollutants, so there is growing interest in the use of enzymatic biodegradation systems based on specific oxidoreductases.

In processes for the enzymatic removal of pharmaceuticals from the environment, several groups of enzymes with high catalytic potential towards biologically active compounds receive special attention. Among the most commonly used enzymes in the decomposition of pharmaceuticals is laccase (EC 1.10.3.2), which is a copper oxidase capable of oxidizing phenolic compounds, aromatic amines, and selected hormones such as ethinylestradiol and its derivatives [16]. Laccase shows particularly high activity in the presence of redox mediators such as 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) or hydroxybenzostriazol (HBT), which enable it to act against more complex and less reactive substrates [17]. This enzyme has found application, among others, in the removal of common analgesics and anti-inflammatory drugs such as ibuprofen, diclofenac and acetaminophen, as well as in the elimination of β-lactam antibiotics.

Another important group of enzymes are peroxidases, including horseradish peroxidase (HRP) and manganese peroxidase produced by white rot fungi [18]. These enzymes catalyse the oxidation reactions of a wide range of pharmaceuticals containing aromatic structures, in the presence of hydrogen peroxide as an oxygen donor. They are used, among others, in the degradation of psychotropic drugs such as fluoxetine, as well as in the neutralisation of cytostatics used in chemotherapy and steroid hormones present in hospital and municipal wastewater [19].

On the other hand, tyrosinases (EC 1.14.18.1) are another group of enzymes that are involved in both the hydroxylation and oxidation of phenolic compounds and aromatic amines. Their activity is particularly applicable to the degradation of pharmaceuticals containing catechol rings, such as certain antidepressants or antiparkinsonian agents [20]. At the same time, tyrosinases are relatively stable and can operate over a wide pH range, which favours their use in environmental conditions.

A special case is cytochrome P450, a complex enzyme systems present in both higher organisms and numerous microorganisms. They are heme-containing monooxygenases that introduce one atom of oxygen into a substrate while reducing the other atom to water, which enables them to catalyze a wide variety of oxidative reactions. These enzymes play a key role in natural detoxification processes, catalysing many biotransformation reactions such as hydroxylations, epoxidations, N- and O-dealkylations [21]. This makes them capable of degrading a wide range of pharmaceutical substances. However, their use in environmental practice faces some limitations—cytochrome P450 has low stability outside the organism and require the presence of expensive cofactors such as NADPH, increasing the cost and difficulty of their commercial application.

Another group of substances whose harmful character can be reduced using enzymes are heavy metal ions, such as lead, mercury, cadmium, arsenic or chromium, which are among the most dangerous environmental pollutants due to their persistence, toxicity and ability to accumulate in living organisms. Unlike many organic compounds, metals are not biodegradable, making their presence in the environment, even in very low concentrations, a serious threat to the health of humans, animals and entire ecosystems. Although enzymes cannot directly degrade heavy metals, they can play an important role in their neutralisation by participating in biochemical reactions that reduce toxicity or facilitate the removal of these elements [22]. One of the most important mechanisms is the reduction of oxidised, more toxic forms of metals to less reactive forms. An example is chromium reductases, which catalyse the conversion of hexavalent chromium (Cr(VI)) to its trivalent, much less toxic form (Cr(III)) [23]. Such a reaction is a key step in the bioremediation of chromium-contaminated environments, especially in the vicinity of plating and tanning plants. Enzymes can also indirectly promote heavy metal detoxification by participating in the biosynthesis of metallothioneins and phytochelatins, which are proteins and peptides that have the ability to bind metal ions and sequester them in cells [24]. These mechanisms make metals less bioavailable, reducing their toxic effects and promoting their safe storage or removal from the body. This distinction is particularly important in comparison with the remediation of organic pollutants: while enzymatic processes can lead to the complete mineralisation of organic xenobiotics into harmless end products such as carbon dioxide and water, heavy metals cannot be chemically eliminated from the environment. Instead, enzymatic activity contributes to their detoxification through redox transformations that mitigate their bioavailability and toxicity but do not remove the elemental contaminants themselves.

Another important process in which enzymes are involved is the synthesis of biopolymers, such as extracellular polymeric substances (EPS), mainly produced by soil and aquatic microorganisms. EPS act as a natural "traps" for metals—they bind and immobilize metal ions in the biological matrix, which reduces their mobility and uptake in the environment [25]. This process is particularly important in the context of stabilising metals in soils contaminated by industrial activities. The use of enzymes in the fight against heavy metal ions pollution therefore does not rely on their degradation, but on their chemical transformation, sequestration or stabilisation, effectively reducing the environmental risks associated with the presence of these elements. Further research into enzyme engineering and environmental biotechnologies can significantly improve the efficiency of such strategies, making them more cost-effective and adapted to real-world conditions.

Plastics, such as polyethylene terephthalate (PET), polyvinyl chloride (PVC) and polyethylene (PE), are widely used in many sectors of the economy for their mechanical, chemical and functional properties. Unfortunately, their exceptional durability comes with serious environmental problems—plastics accumulate in ecosystems, where they can persist for decades. It is estimated that global plastic production exceeds 400 million tonnes per year, of which only a small percentage is effectively recycled, with the rest ending up in landfills or the environment [26]. One of the most promising solutions to this problem is the enzymatic degradation of plastics, allowing them to be broken down to basic monomers that can be reused. Of particular interest are enzymes capable of degrading PET, one of the most widely used polymers in the production of packaging and synthetic fibres. A key enzyme in this process is PETase, which catalyses the hydrolysis of the ester bonds in the polymer chain, leading to the formation of terephthalic acid (TPA) and ethylene glycol (EG)—compounds that can be reused in the synthesis of new PET [27].

The discovery of the bacterium *Ideonella sakaiensis* in 2016, capable of naturally degrading PET using PETase and MHETase (responsible for further degradation of intermediates), opened a new era in research into biotechnological recycling of plastics [28]. Subsequent years brought structural modifications of PETase, leading to variants with much higher enzymatic activity and greater stability under industrial conditions. These advances have made it possible to design enzyme reactors in which the efficient conversion of used plastic to valuable chemical feedstocks takes place [29]. In addition to PETase, other enzymes, such as cutinases, are also being investigated that have the ability to degrade the surface of lower-density plastics such as PE [30]. Although their efficiency is currently lower than that of PET-degrading enzymes, the development of protein engineering methods and combinatorial synthesis opens up prospects for increasing their efficiency.

Today's enzymatic recycling strategies are increasingly taking the form of hybrid technologies, combining enzymatic biodegradation with chemical and material processes such as monomer extraction, their re-polymerisation or conversion into entirely new materials with increased added value. Such approaches are in line with a closed-loop economy (CE) and provide an innovative alternative to traditional mechanical recycling methods.

In practice, the aforementioned enzymes are used both in free form, dissolved in solution, and immobilized on solid carriers, which allows their reuse and increased stability and efficiency of action under varying environmental conditions. Increasing use is also being made of micro-organisms that naturally produce the relevant enzymes or of genetically modified strains designed to enhance the expression of specific degradation pathways. Such approaches form the basis of modern, sustainable technologies for environmental clean-up of micropollutants. The use of enzymatic methods for degradation of toxic pollutants carries a number of advantages, including high reaction selectivity, absence of secondary contamination and the ability to perform processes under environmental conditions. However, implementing these technologies on an industrial scale requires overcoming numerous barriers, such as the limited stability of enzymes under field conditions, sensitivity to inhibitors present in the soil, and production and application costs. Despite these challenges, enzymes represent a viable alternative to traditional methods of chemical cleaning of the environment. Their role in the future may be crucial in the development of precision agriculture, point source bioremediation and the creation of water and soil purification systems that are compatible with the principles of a closed loop economy. Indeed, with enzymes, it is possible to develop biotechnological methods of purifying water and wastewater from harmful substances that pose a serious threat to aquatic ecosystems and public health. The detailed understanding of enzyme mechanisms, substrate specificity, and environmental tolerances thus provides a solid foundation for scaling these processes from laboratory studies to industrial applications.

3. Industrial Use of Enzymes for Micropollutants Removal

Many industries—such as the chemical, textile, petrochemical and food industries—generate wastewater containing numerous compounds resistant to degradation. The most common contaminants include phenols, synthetic dyes, organic solvents, aldehydes and aromatic amines. Conventional treatment methods, based on physical and chemical processes, often prove insufficient or costly, making enzymes an attractive alternative due to their selectivity, efficiency and environmental friendliness.

Primarily, oxidative and hydroxylating enzymes, capable of converting toxic organic compounds into less harmful products, are used in industry. Examples include laccases, which play an important role in the oxidation of phenolic compounds present in, among other things, wastewater from breweries and fermentation plants [31]. The action of these enzymes reduces the toxicity of phenols and facilitates their further biodegradation in biological treatment plants. Another group of enzymes of industrial importance are monooxygenases, which catalyse the hydroxylation of organic solvents and aromatic compounds. This makes it possible to convert persistent and hydrophobic molecules into more soluble and decomposable forms, thereby increasing purification efficiency.

Also of particular interest are dioxygenases, capable of degrading polycyclic aromatic hydrocarbons (PAHs) present in the effluents of the petrochemical and dyeing industries [32]. In the context of the textile industry, it is worth highlighting peroxidases, which are used to degrade azo dyes—some of the most toxic and persistent synthetic compounds. These enzymes, in the presence of hydrogen peroxide, degrade azo bonds and lead to the decolourisation of wastewater. Integrated into flow-through reactors and filtration systems, peroxidases allow efficient treatment of wastewater without the need for strong chemical reactants such as chlorine or ozone, which can generate secondary contamination [33]. Nevertheless, the use of enzymes in industrial wastewater treatment systems is still under dynamic development, but already today their efficiency, selectivity and ability to work in complex industrial matrices make them a viable alternative to classical treatment methods.

4. Challenges and Limitations of Enzyme Technology in Micropollutants Removal

Despite its enormous potential, enzyme technology faces significant limitations. One of the main challenges facing the development of enzyme technology is the limited stability of enzymes under real-world environmental conditions. High or low temperatures, fluctuating pH, the presence of salts, heavy metals or compounds that inhibit catalytic activity can cause a rapid decline in enzyme efficiency, significantly reducing their practical utility. Under laboratory conditions, enzymes usually function under optimal conditions, but in natural or industrial matrices—such as wastewater or soils—these parameters often fluctuate, resulting in a loss of enzymatic activity. Another limitation is the high cost of enzyme production and purification. The processes of microbial fermentation and subsequent isolation and purification of enzymes require high financial and technological investment. This is especially true for high-purity enzymes needed for high-precision applications. As a result, the cost of implementing enzyme technology on an industrial scale is often beyond the capacity of many companies, especially those in the public sector or operating in developing countries. The scalability of enzymatic processes remains an equally important problem. Although many laboratory experiments show very promising results, translating them to production conditions faces numerous difficulties. The scale at which enzymes need to operate in real-world applications requires large volumes, high yields and resistance to technological disruption. Many biocatalytic technologies are still at the pilot stage or require support from additional enabling processes. A final barrier to point out is the narrow specificity of enzymes, i.e., their limited ability to act only on selected, specific chemical compounds. While it is this selectivity that is considered one of the greatest advantages of enzymes, in practice it can limit their usefulness in removing mixtures of contaminants. In many cases, the environment is contaminated with different substances at the same time—pesticides, drugs, metals and microplastics—making it impossible for a single enzyme to provide a comprehensive clean-up. For this reason, intensive research is being conducted into the creation of multi-enzymatic systems, synthetic microbiomes and enzymes with a wider substrate range.

5. Future Trends

In the face of increasing pollution challenges, enzyme technologies are becoming increasingly important as a key component of sustainable development strategies. Advances in fields such as synthetic biology, artificial intelligence and nanotechnology are creating entirely new opportunities to design and refine enzymes with desired properties. Through the use of machine learning algorithms, including deep learning, it is becoming possible to predict the structure of proteins and design "tailor-made" enzymes—with high stability, activity and selectivity towards specific contaminants.

To overcome existing limitations and increase the efficiency of enzymes in environmental applications, a number of advanced technological and research activities are being undertaken. One of the most promising developments is protein engineering, which makes it possible to modify the structure of enzymes at the molecular level [34]. Through the use of genetic engineering methods, such as directed mutagenesis or molecular evolution, it is possible to obtain enzymes with increased thermal stability, a wider pH range of action, resistance to inhibitors or with extended substrate specificity. Biocatalysts optimized in this way can function much more effectively under real-world environmental conditions, as well as exhibiting greater operational durability in industrial processes.

Another strategy to support the practical applications of enzymes is their immobilization, i.e., immobilization on suitable carriers [35]. This process not only increases the stability of enzymes, but also facilitates their recovery and reuse. A variety of carrier materials are used for this purpose, such as alginates, silica gels, synthetic polymers or nanoparticles. Immobilization protects enzymes from denaturation, allows control over their location in the reactor and often has a beneficial effect on their catalytic activity. State-of-the-art intelligent carrier systems are also being developed that respond to changes in the environment, further increasing the precision and efficiency of the purification process [36].

In addition, modern environmental biotechnology is increasingly using advanced protein and microbial engineering tools to develop new, more efficient solutions for environmental clean-up. One of the most promising approaches is the design of so-called on-demand enzymes—specially designed proteins with high specificity towards specific classes of compounds, such as pesticides, pharmaceuticals or microplastics [37]. By using artificial intelligence and tools such as AlphaFold, it becomes possible to predict the spatial structure of enzymes even before they are synthesised in the laboratory, significantly reducing the time and cost of their development.

Another innovative solution is synthetic microbiomes, i.e., artificially constructed consortia of microorganisms that work together to cascade degradation of contaminants. Studies have demonstrated that synthetic microbial communities can enhance plant resilience to environmental stresses by promoting beneficial interactions among microorganisms [38]. Such systems can be extremely useful in chemically complex environments, such as municipal or industrial wastewater, where a single microbial strain or enzyme is often unable to perform complete detoxification efficiently. In synthetic microbiomes, individual microorganisms perform well-defined functions, allowing for increased efficiency and sustainability of the treatment process.

Significant progress is also being made in the field of pollution monitoring through the development of enzyme biosensors. These devices integrate enzymes with modern chemical and optoelectronic detection platforms, enabling the rapid and precise detection of specific substances in the environment in real time. Enzyme biosensors have great potential for practical applications—from continuous monitoring in wastewater treatment plants, to detection of contamination in groundwater, to use in mobile monitoring systems as components of precision agriculture.

Hybrid systems that combine enzymes with other physicochemical technologies—nanomaterials, selective membranes or flow reactors—may also play an important role in the future of environmental biotechnology. Such integrated systems make it possible not only to increase the efficiency of pollutant degradation, but also to improve the stability and durability of enzymes under industrial conditions. For example, immobilization of enzymes on the surface of metal oxide nanoparticles can protect them from denaturation and inhibitor effects, while facilitating their recovery and reuse.

An additional factor supporting the development of environmental biotechnology is the changing legal environment. Increasingly stringent standards for water, soil and air quality and the development of the climate policy of the European Union and other international organizations increase the demand for green technologies. Enzymes—as tools with a low environmental impact—can play an important role in the transformation of industry and municipal economy towards climate neutrality and a circular economy.

Hence, new enzyme technologies have the potential to revolutionize the way we approach environmental pollution problems. Advances in synthetic biology, materials science, and digital technology have enabled the creation of highly specialized and sustainable purification systems that are not only effective but also environmentally friendly.

6. The Role of Enzymes in the Circular Economy

The circular economy is a model of sustainable development that aims to maximize resource use while minimizing waste, energy consumption, and primary raw materials. Instead of the traditional linear model of "take-use-throw away," the circular economy promotes reuse, recycling, and regeneration of products and materials. Enzymes, thanks to their high specificity and effectiveness in mild conditions, are a key tool for achieving the assumptions of this model.

In the context of the circular economy, enzymes are playing an increasingly important role as tools enabling the efficient conversion of waste into secondary raw materials or value-added products. One of the main areas of their application is the bioconversion of organic waste. Hydrolytic enzymes such as cellulases, amylases or proteases catalyze the decomposition of complex biopolymers like cellulose, starch or proteins—contained in agricultural and food waste [39]. As a result of these reactions, simple sugars, amino acids and other metabolites are produced, which can then be used to produce biofuels, bioplastics or organic fertilizers, thus supporting the transformation towards sustainable sources of energy and materials. Another important application of enzymes in the circular economy is the production of biopolymers from plant waste. Enzymatic conversion of lignocellulosic biomass allows the extraction of valuable monomers, such as lactic acid, which is a raw material for the synthesis of biodegradable plastics, e.g., polylactide (PLA). Compared to conventional chemical methods, enzymatic processes are characterized by lower energy consumption, lower pollutant emissions and limited use of toxic reagents, which makes them an attractive alternative from the environmental protection point of view [40].

Enzymes also play an important role in the upcycling of textile materials. In particular, lipases, cellulases and pectinases are used in the gentle decomposition of textile waste, enabling the recovery of cellulose fibres [41]. The raw materials obtained in this way can be reused in the production of new fabrics, composites or insulation materials, contributing to the reduction of the demand for virgin cotton and synthetic fibres, the production of which is associated with the high consumption of water resources and chemicals. The use of enzymes in the depolymerization processes of composite materials, such as multilayer laminates used in packaging, is also worth noting [42]. Thanks to the appropriate selection of enzymes, it is possible to selectively decompose individual material layers—e.g., cellulose, protein or polyester—which allows the recovery of clean fractions of secondary raw materials suitable for reprocessing. This type of approach supports the closing of the material life cycle and minimizes the amount of waste going to landfill. All these processes prove that enzymes are a key element of technological support for the idea of the circular economy, enabling not only effective degradation, but above all the transformation of waste into resources, in accordance with the principle "nothing is wasted in nature". The integration of enzymatic processes with industrial recycling technologies is becoming increasingly feasible thanks to the development of engineering biocatalysis and enzyme immobilization technology. An example of effective application of the circular economy in practice is the enzymatic degradation of PET in a closed cycle of plastic bottle production—a process that allows for the recovery of monomers and their re-polymerization, while limiting the use of petrochemical raw materials. In the longer term, the development of enzymes capable of degrading complex and resistant to degradation materials (such as elastomers, thermosets or electronic waste) may enable a more complete closure of material cycles in various industrial sectors. Thus, enzymes are becoming a strategic tool in the transformation towards a low-emission, resource-efficient and environmentally friendly economy of the future.

7. Conclusions

Enzymes are a powerful tool in the fight against environmental pollution. Their high selectivity, effectiveness in mild conditions and the possibility of application in a variety of matrices make them a real alternative to conventional treatment methods. Although this technology still requires investment and development, its potential is huge. In the future, we can expect an increasing importance of enzymes in wastewater treatment, soil remediation, plastic recycling and urban detoxification. In the era of climate crisis and environmental degradation, innovative enzyme technologies can become one of the pillars of sustainable development. New enzyme technologies have the potential to revolutionize the way we approach environmental pollution problems. Advances in synthetic biology, materials science, and digital technology have enabled the creation of highly specialized and sustainable purification systems that are not only effective but also environmentally friendly.

However, the complexity of the challenges related to bioremediation and environmental remediation means that effective solutions can only be developed within an interdisciplinary approach. An example is the design of enzymatic bioreactors, which require simultaneous consideration of enzyme properties, appropriate flow parameters, durability of construction materials and operating costs. This type of integration of knowledge and competences opens up new possibilities for implementing enzymatic biotechnologies on an industrial scale, taking into account real environmental and economic conditions.

Author Contributions

A.R.: conceptualization, methodology, writing—original draft preparation; J.Z.: conceptualization, visualization, supervision, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. Rathod, S.V.; Saras, P.; Gondaliya, S.M. Environmental Pollution: Threats and Challenges for Management. In *Eco-Restoration of Polluted Environment*; CRC Press: Boca Raton, FL, USA, 2024. ISBN 978-1-00-342339-3.
2. Mejía-Marchena, R.; Maturana-Córdoba, A.; Gómez-Cerón, D.; et al. Industrial Wastewater Treatment Technologies for Reuse, Recycle, and Recovery: Advantages, Disadvantages, and Gaps. *Environ. Technol. Rev.* **2023**, *12*, 205–250. https://doi.org/10.1080/21622515.2023.2198147.
3. Somu, P.; Narayanasamy, S.; Gomez, L.A.; et al. Immobilization of Enzymes for Bioremediation: A Future Remedial and Mitigating Strategy. *Environ. Res.* **2022**, *212*, 113411. https://doi.org/10.1016/j.envres.2022.113411.
4. Yaashikaa, P.R.; Devi, M.K.; Kumar, P.S. Advances in the Application of Immobilized Enzyme for the Remediation of Hazardous Pollutant: A Review. *Chemosphere* **2022**, *299*, 134390. https://doi.org/10.1016/j.chemosphere.2022.134390.
5. Singh, S.; Gupta, A.; Waswani, H.; et al. Impact of Pesticides on the Ecosystem. In *Agrochemicals in Soil and Environment: Impacts and Remediation*; Naeem, M., Bremont, J.F.J., Ansari, A.A., et al., Eds.; Springer Nature: Singapore, 2022; pp. 157–181. ISBN 9789811693106.
6. Sun, M.; Xu, W.; Zhang, W.; et al. Microbial Elimination of Carbamate Pesticides: Specific Strains and Promising Enzymes. *Appl. Microbiol. Biotechnol.* **2022**, *106*, 5973–5986. https://doi.org/10.1007/s00253-022-12141-4.
7. Chia, X.K.; Hadibarata, T.; Kristanti, R.A.; et al. The Function of Microbial Enzymes in Breaking down Soil Contaminated with Pesticides: A Review. *Bioprocess Biosyst. Eng.* **2024**, *47*, 597–620. https://doi.org/10.1007/s00449-024-02978-6.
8. Shukla, E.; Bendre, A.D.; Gaikwad, S.M.; et al. Hydrolases: The Most Diverse Class of Enzymes. In *Hydrolases*; IntechOpen: London, UK, 2022. ISBN 978-1-80355-163-0.
9. Sharma, S.; Bhatt, K.; Shrivastava, R.; Nadda, A.K. Chapter 14-Tyrosinase and Oxygenases: Fundamentals and Applications. In *Biotechnology of Microbial Enzymes,* 2nd ed.; Brahmachari, G., Ed.; Academic Press: New York, NY, USA, 2023; pp. 323–340. ISBN 978-0-443-19059-9.
10. Chen, J.; Guo, Z.; Xin, Y.; et al. Effective Remediation and Decontamination of Organophosphorus Compounds Using Enzymes: From Rational Design to Potential Applications. *Sci. Total Environ.* **2023**, *867*, 161510. https://doi.org/10.1016/j.scitotenv.2023.161510.
11. Sharma, A.K.; Pandit, J. Advanced Bioremediation Strategies for Organophosphorus Compounds. *Microbiol. Biotechnol. Lett.* **2023**, *51*, 374–389. https://doi.org/10.48022/mbl.2308.08011.
12. Łomża, P.; Krucoń, T.; Tabernacka, A. Potential of Microbial Communities to Perform Dehalogenation Processes in Natural and Anthropogenically Modified Environments—A Metagenomic Study. *Microorganisms* **2023**, *11*, 1702. https://doi.org/10.3390/microorganisms11071702.
13. Samadi-Maybodi, A.; Ghezel-Sofla, H.; BiParva, P. Simultaneous Removal of Phenoxy Herbicides, 2-Methyl-4-Chlorophenoxyacetic Acid and 2,4-Dichlorophenoxyacetic Acid from Aqueous Media by Magnetized MgAl-LDH@Fe_3O_4 Composite: Application of Partial Least Squares and Doehlert Experimental Design. *J. Environ. Health Sci. Eng.* **2024**, *22*, 97–121. https://doi.org/10.1007/s40201-023-00877-8.
14. Puri, M.; Gandhi, K.; Suresh Kumar, M. A Global Overview of Endocrine Disrupting Chemicals in the Environment: Occurrence, Effects, and Treatment Methods. *Int. J. Environ. Sci. Technol.* **2023**, *20*, 12875–12902. https://doi.org/10.1007/s13762-022-04636-4.
15. Ismanto, A.; Hadibarata, T.; Kristanti, R.A.; et al. Endocrine Disrupting Chemicals (EDCs) in Environmental Matrices: Occurrence, Fate, Health Impact, Physio-Chemical and Bioremediation Technology. *Environ. Pollut.* **2022**, *302*, 119061. https://doi.org/10.1016/j.envpol.2022.119061.
16. Chmelová, D.; Ondrejovič, M.; Miertuš, S. Laccases as Effective Tools in the Removal of Pharmaceutical Products from Aquatic Systems. *Life* **2024**, *14*, 230. https://doi.org/10.3390/life14020230.
17. Lopes, J.M.; Marques-da-Silva, D.; Videira, P.Q.; et al. Comparison of Laccases and Hemeproteins Systems in Bioremediation of Organic Pollutants. *Curr. Protein Pept. Sci.* **2022**, *23*, 402–423. https://doi.org/10.2174/1389203723666220704090416.
18. Sellami, K.; Couvert, A.; Nasrallah, N.; et al. Peroxidase Enzymes as Green Catalysts for Bioremediation and Biotechnological Applications: A Review. *Sci. Total Environ.* **2022**, *806*, 150500. https://doi.org/10.1016/j.scitotenv.2021.150500.
19. Basumatary, D.; Yadav, H.S.; Yadav, M. The Role of Peroxidases in the Bioremediation of Organic Pollutants. *Nat. Prod. J.* **2023**, *13*, 60–77. https://doi.org/10.2174/2210315512666220410132847.

20. Arrighi, F. New Prospectives on the Benzo[b]Thiophene-3-Ole Scaffold: Design, Synthesis, and Biological Evaluation of Novel Monoamine Oxidase Inhibitors & Photocatalytic Functionalization of Dehydroalanine-Derived Peptides in Batch and Flow. Available online: https://iris.uniroma1.it/handle/11573/1730176 (accessed on 10 May 2025).
21. Mokhosoev, I.M.; Astakhov, D.V.; Terentiev, A.A.; et al. Cytochrome P450 Monooxygenase Systems: Diversity and Plasticity for Adaptive Stress Response. *Prog. Biophys. Mol. Biol.* **2024**, *193*, 19–34. https://doi.org/10.1016/j.pbiomolbio.2024.09.003.
22. Li, Y.; Mu, Z.; Yuan, Y.; et al. An Enzymatic Activity Regulation-Based Clusterzyme Sensor Array for High-Throughput Identification of Heavy Metal Ions. *J. Hazard. Mater.* **2023**, *454*, 131501. https://doi.org/10.1016/j.jhazmat.2023.131501.
23. Sharma, P.; Singh, S.P.; Parakh, S.K.; et al. Health Hazards of Hexavalent Chromium (Cr (VI)) and Its Microbial Reduction. *Bioengineered* **2022**, *13*, 4923–4938. https://doi.org/10.1080/21655979.2022.2037273.
24. Sethi, S. Phytochelatins: Heavy Metal Detoxifiers in Plants. In *Advanced and Innovative Approaches of Environmental Biotechnology in Industrial Wastewater Treatment*; Shah, M.P., Ed.; Springer Nature: Singapore, 2023; pp. 361–379. ISBN 978-981-9925-98-8.
25. Huang, L.; Jin, Y.; Zhou, D.; et al. A Review of the Role of Extracellular Polymeric Substances (EPS) in Wastewater Treatment Systems. *Int. J. Environ. Res. Public Health* **2022**, *19*, 12191. https://doi.org/10.3390/ijerph191912191.
26. Mohajan, H.K. Plastic Pollution: A Potential Threat on Health and Environment. *Stud. Soc. Sci. Humanit.* **2025**, *4*, 25–30.
27. Han, Y.; Wang, R.; Wang, D.; et al. Enzymatic Degradation of Synthetic Plastics by Hydrolases/Oxidoreductases. *Int. Biodeterior. Biodegrad.* **2024**, *189*, 105746. https://doi.org/10.1016/j.ibiod.2024.105746.
28. Khairul Anuar, N.F.S.; Huyop, F.; Ur-Rehman, G.; et al. An Overview into Polyethylene Terephthalate (PET) Hydrolases and Efforts in Tailoring Enzymes for Improved Plastic Degradation. *Int. J. Mol. Sci.* **2022**, *23*, 12644. https://doi.org/10.3390/ijms232012644.
29. Liu, Z.; Chang, S.H.; Mailhot, G. Emerging Biochemical Conversion for Plastic Waste Management: A Review. *Molecules* **2025**, *30*, 1255. https://doi.org/10.3390/molecules30061255.
30. Ali, S.S.; Elsamahy, T.; Al-Tohamy, R.; et al. A Critical Review of Microplastics in Aquatic Ecosystems: Degradation Mechanisms and Removing Strategies. *Environ. Sci. Ecotechnology* **2024**, *21*, 100427. https://doi.org/10.1016/j.ese.2024.100427.
31. Sodhi, A.S.; Bhatia, S.; Batra, N. Laccase: Sustainable Production Strategies, Heterologous Expression and Potential Biotechnological Applications. *Int. J. Biol. Macromol.* **2024**, *280*, 135745. https://doi.org/10.1016/j.ijbiomac.2024.135745.
32. Vijayanand, M.; Ramakrishnan, A.; Subramanian, R.; et al. Polyaromatic Hydrocarbons (PAHs) in the Water Environment: A Review on Toxicity, Microbial Biodegradation, Systematic Biological Advancements, and Environmental Fate. *Environ. Res.* **2023**, *227*, 115716. https://doi.org/10.1016/j.envres.2023.115716.
33. Wan, L.; Jiang, M.; Cheng, D.; et al. Continuous Flow Technology-a Tool for Safer Oxidation Chemistry. *React. Chem. Eng.* **2022**, *7*, 490–550. https://doi.org/10.1039/D1RE00520K.
34. Victorino da Silva Amatto, I.; Gonsales da Rosa-Garzon, N.; Antônio de Oliveira Simões, F.; et al. Enzyme Engineering and Its Industrial Applications. *Biotechnol. Appl. Biochem.* **2022**, *69*, 389–409. https://doi.org/10.1002/bab.2117.
35. Maghraby, Y.R.; El-Shabasy, R.M.; Ibrahim, A.H.; et al. Enzyme Immobilization Technologies and Industrial Applications. *ACS Omega* **2023**, *8*, 5184–5196. https://doi.org/10.1021/acsomega.2c07560.
36. Tadesse, M.; Liu, Y. Recent Advances in Enzyme Immobilization: The Role of Artificial Intelligence, Novel Nanomaterials, and Dynamic Carrier Systems. *Catalysts* **2025**, *15*, 571. https://doi.org/10.3390/catal15060571.
37. Tang, C.; Wang, L.; Zang, L.; et al. On-Demand Biomanufacturing through Synthetic Biology Approach. *Mater. Today Bio* **2023**, *18*, 100518. https://doi.org/10.1016/j.mtbio.2022.100518.
38. Liang, Y.; Ma, A.; Zhuang, G. Construction of Environmental Synthetic Microbial Consortia: Based on Engineering and Ecological Principles. *Front. Microbiol.* **2022**, *13*, 829717. https://doi.org/10.3389/fmicb.2022.829717.
39. Ashokkumar, V.; Flora, G.; Venkatkarthick, R.; et al. Advanced Technologies on the Sustainable Approaches for Conversion of Organic Waste to Valuable Bioproducts: Emerging Circular Bioeconomy Perspective. *Fuel* **2022**, *324*, 124313. https://doi.org/10.1016/j.fuel.2022.124313.
40. Ekeoma, B.C.; Ekeoma, L.N.; Yusuf, M.; et al. Recent Advances in the Biocatalytic Mitigation of Emerging Pollutants: A Comprehensive Review. *J. Biotechnol.* **2023**, *369*, 14–34. https://doi.org/10.1016/j.jbiotec.2023.05.003.
41. Zafar, M.G.; Mumtaz, A.; Akbar, A.; et al. Distinctive Role of Enzymes in Textile Industry. In *Enzymes in Textile Processing: A Climate Changes Mitigation Approach: Textile Industry, Enzymes, and SDGs*; Arshad, M., Ed.; Springer Nature: Singapore, 2025; pp. 1–17. ISBN 978-981-9780-58-7.
42. Rezvanian, K.; Shahan, H.T.; Ghofrani, D.; et al. Innovative Manufacturing and Recycling Approaches for Multilayer Polymer Packaging: A Comprehensive Review. *Polym. Plast. Technol. Mater.* **2025**, *64*, 1441–1474. https://doi.org/10.1080/25740881.2025.2470852.