Proceedings of CONF-FMCE 2025 Symposium: Semantic Communication for Media Compression and Transmission
DOI: 10.54254/2755-2721/2025.GL29004

Molecular Mechanism of Enzymatic Degradation of Environmental Pollutants

Danni Xie

Montini Catholic High School, Lombard, USA
xieyouqi2@gmail.com

Abstract. Due to the flourishing of industrialization, urbanization and other activities, environmental pollution has been intensified and followed by diverse organic pollutants including the residues of pesticides and the products resistant to biodegradation that still constitute a continuous threat to environmental and human health. The discovery that enzymes help with environmental pollution is eye-catching. In contrast to conventional physicochemical treatment technology, enzymatic destruction has gradually become a research focus in dealing with environmental pollution in recent years because of high efficiency, specificity, milder and environmentally-friendly properties. Studies in this area of enzymatic degradation of environmental pollutants focus on the catalytic mechanism of oxidoreductases and hydrolases, roles of coenzymes and catalytic active sites, the influence of genetic regulation and molecular evolution in the enzymatic reactions are reviewed in this paper. It further reviews the state-of-art of enzymes in wastewater treatment, solid waste management and soil remediation, and major challenges and further development trends of them in this area.

Keywords: enzyme catalysis, biodegradation, environmental pollutants, molecular mechanism, bioremediation

1. Introduction

Environmental pollution is a critical problem in the world, and human beings are increasingly threatened by the increasing global environmental pollution caused by the popular use of petrochemical raw materials, agricultural pesticides, dyes, drug waste, polyethylene, and other materials, and has caused large quantities of long-polluted difficult-to-degrade pollutants into the environmental ecosystem. Not only human society, but also has a serious impact on human health. Even though conventional treatment processes, such as chemical oxidation, incineration and physical adsorption, can alleviate certain pollutants to some extent, but have serious limitations in high consumption of energy, toxic by-products and/or uncompleted treatment.

As has been pointed out, enzymes are important for environment pollution control by their nature of high-efficiency, high selectivity, mild reaction conditions, environmentally friendly, renewable etc. Systematically studying the molecular mechanism of enzymatic degradation reaction will not only revealing their catalytic mechanism but also offer theoretical support for artificial modification and practical usage of novel high-efficiency enzymes.

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2025.GL29004

2. Basic information about enzymes

Enzymes are principally proteins (some exceptions are made of RNA, acting as highly efficient catalysts in the organism: By decreasing the activation energy, they accelerate every chemical process. Within the classification of the International Enzymology Committee, enzymes belong to one of six classes: Oxidoreductases catalyze the transfer of electrons (cytochrome oxidase is an example in the respiratory chain). Transferases cause the transfer of groups (e.g., urease). Isomerases introduce isomeric transformations in biomolecules (e.g., isomerase from the glycolytic pathway). Lyases are able to cleave groups that are released without a transfer reaction (e.g., proline). Ligases combine several components by dephosphorylation (e.g., ATPases). ,Hydrolases split chemical bonds by hydrolysis (e.g., lysozyme). e.g., transaminases controlling the metabolism of amino acids), hydrolases: hydrolyse the chemical bonds (e.g., amylase for polysaccharides), lyases: initiates the cleavage of the carboncarbon bond (e.g., aldolase in the metabolism of carbohydrates), isomerases: changes the conformation of molecular structure (phosphoglucoevolase, for instance, keeps the balance of the glycolysis), ligases: creates new molecules (e.g., DNA ligase fixes genetic damage). The enzymes realize their diverse catalytic activities respectively, thus together composing the complex living organism metabolic network.

2.1. The role of oxidases

2.1.1. Typical oxidoreductases and their characteristics

The oxidase enzymes are the most important group of enzymes for destroying environmental pollutants. General examples are laccase, peroxidase, cytochrome P450 and so on. Laccase is a copper-containing polyphenol oxidase capable of catalyzing the oxidation of various phenolic compounds, aromatic amines and non-phenolic substrates, as well as the formation of water from oxygen [1]. Peroxidase acts on H_2O_2as acceptor of electrons to oxidize substrates for contaminant removal of phenols or dyes. Cytochrome P450 is a heme-oxidase that is a superfamily of monooxygenase oxidases with a wide range of substrate specificity, which is involved in the process of oxidative metabolism of various endogenous or xenobiotic compounds (antibiotics, herbicides, alcohols, phenols, drugs, carcinogens and environmental pollutants [2].

2.1.2. Catalytic mechanism

Oxidases such as oxidase enzymes, peroxidase enzymes, laccase, and other redox enzymes, are involved in reduction-oxidation (redox) reactions through an electron transfer process and through cleavage of aromatic bonds. Laccase was catalyzed by the coordinated movement of four copper ions. When the substrate molecules attach to the active site in laccase and transfer an electron to its three-nuclear copper cluster, the laccase is oxidized. Oxygen at the active center then gets reduced to water which rest the laccase back in the initial form for the next catalysis. In the course of it, electrons are lost from the substrates during oxidation, eventually breaking chemical bonds and smaller degraded molecules [3]. Cytochrome P450 uses NADPH-cytochrome P450 reductase as electron donor that can oxidize the substrate to produce hydroxylated and epoxidized products in order to decrease the toxicity, increase water-solubility and help the compounds for further degradation, metabolism, and excretion [4].

DOI: 10.54254/2755-2721/2025.GL29004

2.2. The role of hydrolases

2.2.1. Common hydrolytic enzymes and their functions

Hydrolases mainly degrade organic pollution by cutting off the intermolecular chemical bonds like ester and peptide bond, and its main kinds are lipases, esterase and protease. Lipases can hydrolyze and promote hydrolysis in vivo, catalyzing the breakdown of fats into glycerol and fatty acid, which is widely used in the process of degrading pesticide and plasticizer with ester bond, and have a good enhancement effect for degradation process of pesticide Rodanol and dimethyl diiodopropionic acid [5]. Esterase has higher substrate specificity, can hydrolyze different kinds of ester substances, such as organophosphorus pesticides and artificial esters [6]. Proteinase hydrolyze protein by decomposing peptide bonds in the molecules into peptide and amino acid, and can be used to treat nitrogenous organic substances including protein-containing waste water and biological sludge [6].

2.2.2. Substrate specificity and molecular modification

Hydrolytic enzymes are substrate specific, thus each of them has different recognition and catalysis ability with the associated different types of substrate and chemical bond. Yet this type of substrate specificity also narrows the applications of these hydrolytic enzymes. By rational molecular engineering, the specificity and adaptability of hydrolytic enzymes can both be improved [7]. For example, mutation of strategic amino acids in the catalytic cores of selected lipases may be made by protein engineering techniques to improve substrate specificity and catalytic abilities of lipases towards various ester substrates; and the functional domain of lipases as well as of other hydrolases may be combined (with the help of gene fusion techniques) in multifunctional enzymes for high activity in degradation of wide ranges of substrates.

3. Optimization method

3.1. Co-factors and active centers

3.1.1. Function of cofactor

Metal ions (Fe, Cu, Mn), organic cofactors (FAD, NADH) are required by the activities of many enzymes. It can be noted that metal ions (especially Fe, Cu, Mn) play an important part in enzyme reaction [8]. Since metal ion stabilizes the spatial structure and keeps active conformation of enzymes in the enzymatic system. It also directly involves in the process of electron transfer or proton transfer reaction, thus completing the enzymatic processes. For example, copper ions in laccase form co-ordination with amino acid residues in enzyme protein stabilizing the enzyme structure and conformation to maintain catalytic activity. Iron ions in peroxidase can change the oxidation state which carry electrons transfer and break down of the hydrogen peroxide under the catalytic action.

Catalytic reaction of enzymes is performed by organic co-factors like FAD and NADH. FAD (flavin adenine dinucleotide) as an electron donor plays a part in different types of electron transfer reactions or proton transfer reactions. In glucose oxidase FAD accepts an electron from glucose while the catalysis reaction is oxidized into FADH to transfer an electron to oxygen to form peroxide [9]. In the meanwhile NADH participates in dehydrogenation reactions, functioning as hydrogen donor agent to give energy to other enzymatic reactions.

DOI: 10.54254/2755-2721/2025.GL29004

3.1.2. Structure and function of the active center

The functional site (or the active center) of an enzyme is the region on an enzyme molecule where it directly binds to its substrate and performs the reactions. The conformation of its amino acid residue determines the substrate binding affinity and catalytic efficiency. Generally, these active sites are usually constituted by a small number of amino acid residues that will form a compatible binding site with substrate molecules based on a particular spatial order and chemical feature. Catalytic triad of trypsin The active site of trypsin contains three functional amino acids (i.e., the catalytic triad) which synergistically mediate the hydrolysis of peptide bonds [10]: Serine's hydroxyl group serves as the nucleophile that attacks the peptide bond carbonyl carbon; histidine controls the acid–base balance of the reaction by taking up and giving away protons; aspartic acid stabilizes histidine's charge state, accelerating its ability to transferprotons .

The enzyme's active site residues can bring increased substrate affinity through non-covalent interactions (hydrogen bonding and hydrophobic interactions). At the same time, the three dimensional structure of the enzyme's active site plays the major role in the substrate selectivity.Differences in the structural design of active centers of different enzymes lead to specific recognition and catalytic functions of the substrates involved and hence, evidence the great specificity of enzymatic reactions.

3.2. Gene regulation and molecular evolution

3.2.1. Effect of genetic regulation on enzyme performance

Not only based on its structural elements, the enzyme's activity and stability are controlled by the enzyme's gene itself. At several levels of regulation, their activity and catalytic ability are determined based on the level of gene expression, with the levels of some gene expressions influenced by environmental factors, such as the temperature, pH, and levels of pollutants. These signals induce signaling pathways to modulate the transcription factor activity of the genes of enzymes and regulate transcription rates of those genes. For example, when bacteria encounter pollution with high levels of heavy metal, these bacteria are able to up-regulate their tolerance and detoxification capacity against heavy metal via activating the transcription factors, which leads to increasing transcription of the metallothionein genes [11].

The translated enzyme protein can also be further processed or modified, such as phosphorylation, glycosylation and acetylation, which change enzyme activity, stability and intracellular localization. Specifically, the phosphorylation changes the protein conformation and catalytic activity. Depending on the particular kinase activity, phosphorylation can change enzyme activity. Moreover, individual residues such as serine, threonine or tyrosine in the enzyme protein are possibly phosphorylated by the kinase, as activating or restraining enzymes.

3.2.2. Molecular evolution and enzyme performance optimization

The directed evolution and the genetic engineering strategies can also be used to alter and increase the substrate specificities and the tolerance of enzymes for their activities enhancement in the actual milieu. The directed evolution method can be seen as a gene-engineering model of the natural evolution process; random mutagenesis and screening can be used to search for better-function enzymes out of the abundant mutants. For example, the wild-type lipases have been modified by directed-evolution to produce those lipases with higher activity that will be stable for high

DOI: 10.54254/2755-2721/2025.GL29004

temperatures, pressure, salinity and organic solvents. After several rounds of mutation and selection, the modified lipases may be used in many industrial sectors.

A common technique gene engineering technology achieves specific manipulation of enzymes (by means of gene cloning, site directed mutagenesis and genetic splicing), which can serve to modify functions of the enzymes with a high accuracy (by specific amino acid replacement and related domain addition), enabling the modification of many desired characteristics of enzymes [12]. For example, through the combination of various organisms' functional domains, functional proteins with new functions will be constructed. Together with appropriate properties, new enzymes with combined functions can promote handling of some complex pollutants better. We think that combining molecular evolution and genetic engineering makes room for synthetic biology to create novel functional enzymes leading to a new generation of highly effective and specific enzymes in the fight against ever-increasing environmental disasters.

4. Application prospect

4.1. Waste water treatment

4.1.1. Dye removal wastewater

Complex components, dark coloration, strong toxicity and the enormous challenge of biochemical treatment make dye wastewater one of the greatest challenges in handling industrial wastewater. The enzymatic degradation technology with advantages such as certain highlights for dye wastewater management has been presented. Laccase and peroxidase enzymes are two prominent enzymes in the field of dye degradation. Laccase is responsible for the oxidation reactions of numerous phenolic/non-phenolic dyes into smaller fragments by giving (accepting) electrons to (from) dye molecules, resulting in both a decrease of the color intensity and toxicity [13]. For example, the removal of azo-dye containing wastewater is conducted by laccase reduction of azo bonds in dyes thus forming molecules without any color intensity and increasing the degree of mineralization to CO2 and water. Hydrogen peroxide acceptors, such as the catalase-like peroxidase, also promote oxidative chain growth and ring-opening polymerization of dye molecules with acceptable by-products, which are colorless or low-toxicity.

4.1.2. Degradation of pharmaceutical residues

The pollutants of pharmaceutical wastewater include the organic pollutants PAHs, PCB, TCA, they have strong biological toxicity, but are difficult to degrade and even accumulate in organisms and the environment, and will be harmful to humans and life. The enzymatic degradation technology can effectively realize the depharmaceuticalization. In particular, some specific oxidoreductase or hydrolase has selective activity for breaking specific bonds in drug molecules. As an example, cytochrome P450 enzymes are able to metabolize numerous drugs by introducing functional groups, such as hydroxyl and epoxy groups, rendering a better water-solubility and thus they will become easily removed by subsequent biological treatment [6]. Esterase and amidease belong to the class of hydrolyses, which are capable of cleaving ester and amide bond, thereby reducing large drug molecules into smaller alcohol, acid or amine derivative, which are less toxic and biologically inactive.

DOI: 10.54254/2755-2721/2025.GL29004

4.1.3. Treatment of industrial organic pollutants

Industrial production releases organic pollutants such as phenols, aldehydes, ketones, and polycyclic aromatic hydrocarbons (PAHs), which are carcinogenic, teratogenic, and mutagenic, posing threats to both the environment and human health. Enzymatic degradation effectively breaks down these industrial organic contaminants. For instance, manganese peroxidase catalyzes the oxidation of various phenolic compounds and aromatic substances, progressively degrading pollutant molecules into CO2 and H2O through a free radical mechanism [14]. In the degradation of PAH-containing industrial wastewater, laccase and lignin peroxidase also play significant roles—such as reducing their toxicity and persistence by breaking the aromatic rings in PAHs. Compared with traditional physicochemical treatment methods, enzymatic degradation offers milder reaction conditions, lower energy consumption, and no secondary pollution, making it more suitable for industrial organic pollutant treatment.

4.2. Solid waste degradation

4.2.1. Plastic degradation

The extensive applications of plastics and its products have led to massive "white pollution", occupied area of land through landfill and burning plastic and led to emitting toxic gas and leachate causing another environmental pollution. Enzymatic degradation has also showed effective results in the field of plastic waste degradation as a greener solution. It is known that hydrolases and oxidoreductases are specific types of enzymes which can lead to plastics degradation by cleavage enzymes of specific plastic (i.e., such as, PET, polylactic acid, polyethylene, polyurethane, polyamide, nylon, polyisoprene and nylon in which hydrolases and oxidoreductase enzymes were reported the degradation of polylactic acid by three related enzymes such as γ-(cytochrome c electron transfer) [8]. Esterases (lipases, esterase), hydrolyzing ester bonds in PET molecules, break PET polyethylene terephthalate (PET) into smaller monomers and terephthalic acid [15]. Also, keratinases from a specific category of microorganisms are able to degrade the plastic molecular structure faster. Introduction of genetically engineered enzymes to increase degradation rate and substrate selectivity will be the new avenue in the context of plastic pollution.

4.2.2. Pesticide residues disposal

The more widespread use of pesticides has resulted in pesticide residues in soil and water bodies, which may bring certain risks to ecological and food safety. Enzymatic degradation technology can effectively decrease the environmental risks brought about by pesticides; among enzymes, redox enzyme and hydrolase were the most effective ones. Organic phosphorus hydrolases specifically break down the phosphorus-oxygen or phosphorus-sulfur bonds of the organophosphorus compounds, forming less or non-toxic metabolites (such as phosphate and alcohol) through the hydrolysis [16]. The oxidative enzymes, such as peroxidase or laccase, can degrade the pesticide molecules by reacting with aromatic rings or adding oxygen-containing functional groups, leading to decrease the biological activity and toxicity. Integrating microbial remediation with enzymatic degradation improves the biodegradation efficiency of pesticide residues and realizes a comprehensive control of soil–water system ecology.

DOI: 10.54254/2755-2721/2025.GL29004

4.3. Soil remediation

4.3.1. Oil-contaminated soil remediation

Petroleum pollution by spill of oil and petroleum stored and transported can destroy the ecological functions of soil and affect the growth of crops [10]. Enzymatic technologies show an especial capability for the treatment of petroleum-contaminated soil [11]. Petroleum pollutants can be degraded by microbial enzymes such as hydrocarbon-containing alkane, alkene, and aromatic hydrocarbons [11]. For example, oxygenase enzymes lead oxygen addition reaction on petroleum hydrocarbons, and bring in the hydroxyl groups, which can improve the degradation of microorganisms. Using microorganism or enzymatic agents that have better degrading ability to petroleum pollutants is important for increasing the efficiency of soil remediation [17]. Immobilized enzyme and microorganism can be used to extend the treating time to improve their effectiveness for treatment. Using a proper carrier (nanomaterial, porous polymer etc.) We immobilize enzymes to enhance enzyme stability and reusability so that the enzyme system can continuously apply in soil environment and petroleum pollutants are efficiently biodegraded when conjugated with each other.

4.3.2. Remediation of soil contaminated by polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) are persistent organic pollutants with carcinogenic, teratogenic and mutagenic potentials and are ubiquitous in industrially contaminated soils. Enzymatic degradation is a major remediation tool. Redox enzymes such as laccase, lignin peroxidase and manganese peroxidase employ free radical mechanism to degrade the PAH molecules by cleaving its aromatic rings into toxic or non-toxic metabolites [15]. It was proved that adding microbial population/enzyme supplement containing this group of enzymes to the contaminated soils as biostimulation leads to a decrease in PAHs concentrations and combination of measures on soil which can be considered as a biostimulation strategy includes nitrogen/fertilizer enrichment, adjusting the soil acidity/pH as well as optimizing the management of soil ventilation can be considered as a bio-enhancement measure to increase the efficiency of enzymatic degradation of PAHs.

4.4. Industrial applications

4.4.1. Continuous decomposition treatment in bioreactors

The continuous degradation of pollutants by bioreactors is a good and convenient industrial production method. Using immobilized enzymes in bioreactors can achieve recycling and ensure the stable catalytic activity of enzyme, thus improving the treatment efficiency of pollutants. The immobilized enzymes can choose carriers such as activated carbon, silica gel, sodium alginate gels etc, and immobilize enzymes on them by physical adsorption, chemical covalent bonding or encapsulation. In bioreactor, the mixture of wastewater or exhaust gas containing pollutants continuously moves across the immobilized enzyme bed, enzymes perform the reaction of degradation, and generate harmless or little toxic product [18]. An optimal combination of design conditions such as reaction temperature, pH and flowrate can make the enzymatic degradation process work at high efficiency, which can satisfy the demands of large-scale industrial pollution control.

DOI: 10.54254/2755-2721/2025.GL29004

4.4.2. Nanomaterials as enzyme carriers

Nanomaterials have special physicochemical properties including huge specific surface area, good dispersion ability, controllability of material surface property, etc., so they are good carriers for enzymes. Immobilization of enzymes on nanomaterials increases enzyme stability, reuse ability, the opportunity to interact with substrate, and reaction efficiency. For example, magnetic nanoparticles not only can separate quickly under the action of an external magnetic field, but also promote the dispersion of enzymes into the reaction system to increase the catalytic reaction [19]. Carbon nanotubes and graphene with good biocompatibility and high specific surface areas as superior attachment points for enzyme, can also effectively increase the catalytic activity.Combining the enzymatic degradation technology with the nanomaterials is a new field to develop. The combined technology with nanomaterials not only has the potential to improve the efficiency of pollution treatment and cut the cost of some industrial applications, but also can enhance the pollution degradation efficiency and reduce the cost for industrial usage.

5. Conclusion

Biological mechanisms for the degradation of environmental pollutants that predominantly take place at the molecular level through redox and hydrolysis pathways are driven by cofactors, active sites and genetic regulation. Such enzymes have shown considerable potential for use in the treatment of polluted water and soils and also in waste incineration and in incineration in composting for municipal solid waste. Even in spite of such obstacles for stability and the economy, in the future environment management , enzymatic degradation will probably play an increasing pivotal role. The sustainable enzymatic degradation, together with advances in bioengineering and the interdisciplinary technologies, will be made available and ready-to-use by the respective state or market.

Although enzymatic degradation possesses a bright prospect, a series of issues have not been overcome:natural enzymes are generally unstable in a complex environment;due to the high mass-production and the high usage costs, however, they are rarely used in engineering processes.Our future work might be achievable by: protein engineering/synthetic biology to stabilize and improve specificity of enzymes; creating multi-enzyme synergy for mimicking natural complicated degradation processes; and application of artificial intelligence integrated with nanotechnology for new enzyme design and immobilization.

References

[1] Li Xinyi, Shao Jiawei, Li Jianzhang. Research progress on enzymatic modification and its application in protein-based adhesives. Journal of Forestry Engineering, 2024, 9(05): 13-26.
[2] Song Zhan, Gao Xin, Wu Mian, Lu Fuping, Qin Huimin. Advances in the structure, function, and application of cytochrome P450 enzymes. Microbiology Bulletin, 2020, 47(07): 2245-2254.
[3] Su Jing. Study on the Modification of Laccase and Its Catalytic Mechanism for Aromatic Compound Polymerization . Jiangnan University, 2019.
[4] Liao Huanxin. Chemical/enzyme synergistic catalysis of NAD(P)+ regeneration and application. South China University of Technology, 2021.
[5] Yang Zhong. Research on the synthesis of polyester as plasticizer catalyzed by lipase. Beijing University of Chemical Technology, 2021.
[6] Gao Renjun; Luo Guimin; Li Quanshun; Li Zhengqiang. Enzyme Engineering. Chemical Industry Press: 202310 438.
[7] Dong Hui. Enzyme Activity Analysis and Application Research Based on Multifunctional Polymer Dots. University of Science and Technology of China, 2024.

DOI: 10.54254/2755-2721/2025.GL29004

[8] Sun Yan. Principles and Methods of Enzyme Engineering. Chemical Industry Press: 202307 402.
[9] Zhang Zhen, Wang Haoqi, Gao Yaxin, Yang Pengkun, Sun Yujiao, Qiu Chenxi, Wang Yongfen. Research progress on the physicochemical properties, mechanism of action, and application of glucose oxidase in animal production. Feed Research, 2025, (15): 163-169.
[10] Li Wei. Screening of Trypsin-Producing Bacteria, Fermentation Optimization, and Enzymatic Properties. Jiangnan University, 2015.
[11] Zhou Liuting, Chu Wei, Huang Xiaoyun, You Xiaofeng, Luo Tao, Zeng Xibai, Huang Xiusheng. Advances in the study of mechanisms of phytoremediation of heavy metal contaminated soil. Environmental Science, 1-21.
[12] He Shucheng. Establishment and Application of a Method for Identifying Key Amino Acids for Directed Evolution of Proteins Based on Sequence and Structure Analysis. Hubei University, 2024.
[13] Wang Dan, Xiao Yuanshu, Song Junyan, Zhu Ruofei. Laccase-catalyzed oxidative degradation of octylphenol in printing and dyeing wastewater. Printing and Dyeing, 2025, 51 (08): 63-67.
[14] Cheng Huijun. Removal Methods and Mechanism Analysis of Phenolic Pollutants in Coal Chemical Wastewater. Polyester Industry, 2025, 38 (04): 130-132.
[15] Fu Baotong, Wang Na, Fan Jingwen, Qiao Hui, Han Huawei, Li Xiangkai. Advances in the catalytic mechanism and application of plastic degrading enzymes. Chinese Journal of Biotechnology, 1-27.
[16] Yin Xinlei, Wang Lei, Cai Baiyan. Inhibitory effect of antibiotics on organophosphorus biomineralization in farmland soil. Journal of Ecotoxicology, 1-15.
[17] Yu Jia-Shuai. Metagenomic Analysis of Biodegradation and Remediation of Oil-Contaminated Soil with Different Nutrients. Liaoning Technical University, 2024.
[18] Wang Pingyue. Study on the Conversion of Resveratrol Glucoside in Mulberry by High Mass Transfer Fixed Enzyme Bioreactor.Jiangsu University of Science and Technology, 2024.
[19] Xu Bingbing. Study on the Properties of Proteins Extracted from Streptomycin Fermentation Residue by Enzymes Immobilized on Magnetic Nanocarriers. Hebei University of Science and Technology, 2024.