Application of Nano-catalysts in Biotechnology and Chemical Technology

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Abstract. In the field of biotechnology, nano-catalyst, by virtue of their size effect, high specific surface area and modifiability, can effectively treat infectious diseases, intervene in neurodegenerative diseases, delay the progress of cardiovascular diseases, repair and regenerate bone and skin, and solve the problems such as drug resistance, targeting, and biocompatibility of traditional therapies by catalyzing the generation of active oxygen, scavenging free radicals and other mechanisms in non-tumor medicine; simultaneously enhancing technological performance in biosensing, drug delivery, and pollutant biodegradation, providing support for biotechnology innovation. In the field of chemical engineering, nano-catalysts play a significant role: in chemical synthesis, the rich active sites with high specific surface area can improve reaction rate and selectivity in processes such as ammonia synthesis and methanol production, reduce activation energy, decrease by products, improve raw material conversion rate, and reduce costs; In terms of green chemistry, we aim to promote environmentally friendly production, such as efficiently catalyzing the degradation of organic pollutants in wastewater to reduce the use of chemical reagents; In the field of energy and chemical engineering, it is applied in fuel cell electrode catalysis, photocatalytic hydrogen production, etc., to improve energy conversion efficiency, promote clean energy development, and support the efficient, green, and sustainable development of the chemical industry.

Keywords: Nano-catalyst, biotechnology, medical application, infectious diseases.

1. Introduction

Breakthroughs in biotechnology across medical and environmental fields urgently require addressing the inherent limitations of traditional catalytic systems: natural enzymes are prone to environmental-induced inactivation and difficult to recover, while chemical catalysts lack sufficient targeting specificity and biocompatibility, hindering technological advancement towards high precision and efficiency. The emergence of nano-catalysts provides a critical solution. Their 1-100 nm scale grants an ultra-large specific surface area, enabling abundant active sites to enhance catalytic efficiency. Additionally, their easily modifiable surfaces allow precise targeting, while chemical stability adapts them to complex biological environments. Since the concept of "nanozymes" was proposed in the 1980s, their applications have expanded from fundamental biocatalysis to core fields like non-oncological medical treatment, biosensing, and pollutant degradation [1]. Through synergistic interaction with biomolecules, they have completely revolutionized traditional catalytic models. It should be clearly stated that nanozymes are one of the important branches of nano-catalysts: nano-catalysts are a general term for nanoscale materials with catalytic activity, while nanozymes specifically refer to a class of nano-catalysts that possess both the characteristics of nanomaterials and the catalytic functions of biological enzymes, and the two have a "subordinate relationship" [2].

Based on this, this article systematically sorts out the status, mechanism of action, and research progress of nano-catalysts (with nanozymes as the core representative) in biotechnology. It not only demonstrates the new vitality injected into the development of the field by such materials that combine nanoscale properties and catalytic functions but also looks forward to the challenges they will face in the future and the key directions for development. This article aims to systematically review the current applications of nano-catalysts in biotechnology, with a focus on analyzing their mechanisms of action in core scenarios such as non-oncological medical treatment, biosensing, and pollutant biodegradation [3]. It elucidates the synergistic principles between the size effects of nanomaterials, surface modification characteristics, and biological systems. By summarizing the advantages of nano-catalysts over traditional catalytic materials, the study highlights their crucial value in overcoming bottlenecks in biotechnological development. Additionally, it explores challenges currently faced in nano-catalysts regarding biocompatibility and large-scale application, while also envisioning future research directions and application prospects. The work provides theoretical references and practical guidance for academic research and technological transformation in related fields.

2. The Characteristics of Nano-catalysts

Nanomaterials hold immense application potential due to their nanoscale structure and excellent physicochemical properties. With the advancement of nanotechnology, nano-catalysts, as a new type of material distinct from traditional bulk/micron-scale catalysts, have significantly enhanced catalytic efficiency and selectivity by virtue of their high specific surface area, abundant active sites, and unique electronic structure. They effectively address issues associated with traditional catalysts, such as low activity, harsh reaction conditions, and narrow substrate applicability, thus finding increasingly widespread use in the field of catalysis. In recent years, the simultaneous progress of nano-catalysis and nanomedicine research has driven breakthroughs in the application of nano-catalysts in the biomedical field [4]. Typical nano-catalysts like TiO_2, CeO_2, and Fe_3O_4 can regulate the local microenvironment (e.g., adjusting reactive oxygen species and pH values) through in vivo catalytic reactions to achieve therapeutic effects. "Nano-catalytic therapy" converts endogenous/deliverable substances into therapeutic agents, precisely regulating the chemical properties of biological systems [5]. This provides a highly effective therapeutic strategy with low side effects for pathological abnormalities such as cancer, bacterial infections, inflammation, and brain injuries.

However, nano-catalysts still have room for improvement. The disordered distribution of active sites leads to insufficient catalytic directionality; some multi-metal catalysts exhibit low metal atom utilization, which increases costs and poses risks; they tend to agglomerate and degrade in organisms, resulting in insufficient stability; improper size, surface charge, or modification may trigger toxicity issues like immune rejection and organ accumulation, limiting their clinical translation [6]. Current research is focused on multi-dimensional improvements: optimizing crystal structures, surface defects, and doping to enhance catalytic directionality and atomic utilization; developing core-shell structures and biocompatible coatings to improve stability; screening low-toxicity materials, regulating surface charge, and designing degradable structures to reduce toxicity; and integrating targeted delivery technologies to enhance the enrichment efficiency at lesion sites, thereby promoting their clinical application.

In biotechnology applications, nano-catalysts demonstrate remarkable potential through their unique advantages. Their ultra-small size (1-100 nm) provides an exceptionally large specific surface area, enabling more active sites and significantly enhancing catalytic efficiency. The easily modified surfaces of nanomaterials allow precise binding with biomolecules like enzymes and antibodies, achieving targeted catalysis while minimizing non-specific interference with biological systems. Additionally, nano-catalysts exhibit excellent stability and reusability, capable of withstanding complex biological environments such as pH variations and protease degradation in bodily fluids. This addresses the challenges of natural enzymes being prone to inactivation and difficult to recover, making them irreplaceable in fields like biosensing, drug delivery, and pollutant biodegradation [7].

The development of nano-catalysts in biotechnology can be traced back to the 1980s, when early research focused on the biocatalytic properties of metal nanoparticles such as gold and silver nanoparticles. In 1989, scientists first demonstrated that gold nanoparticles could mimic peroxidase activity, marking the beginning of "nano-catalyst" research. Since the 21st century, breakthroughs in nanoscale fabrication techniques (such as sol-gel methods and bio-templating) have enabled more precise control over the morphology and size of nano-catalysts. The first immunological detection method based on nano-catalysts emerged in 2007, propelling their clinical application. Recent years have seen the development of composite nano-catalysts (e.g., nanoparticle-enzyme conjugate systems) that integrate the strengths of nanomaterials and biomolecules, continuously expanding their applications in cutting-edge biotechnologies like gene editing and cellular regulation [8].

3. Nano-catalysts in Biotechnology

Biotechnology is an interdisciplinary field that integrates theories and technologies from biology, chemistry, engineering, and related disciplines. This field focuses on microorganisms, animal and plant cells, and their components (such as enzymes, genes, proteins) as the core research objects. By designing, modifying, or utilizing their structural functions, target substance transformation, large-scale production of biological products, and specific biological function regulation can be achieved [9].

In the application system of technology, nano-catalysts, as new functional materials, are providing key support for the efficiency improvement of biotechnology. With its characteristics of ultra-high specific surface area, high catalytic activity, and selectivity, it plays an important role in multiple sub fields: in drug development, it can accelerate the synthesis reaction of active ingredients, reduce reaction energy consumption and by-product generation, such as assisting in the efficient preparation of targeted drugs; In the field of environmental remediation, it can enhance the biodegradation process, quickly decompose difficult to degrade pollutants (such as organic pesticide residues and industrial toxic organic compounds) in water or soil, and improve the efficiency of wastewater purification and soil remediation; In the industrial biomanufacturing process, the biological fermentation and enzyme catalysis system can be optimized to improve the conversion rate and yield of products such as biofuels and bio-based chemicals, further promoting the green upgrading of industrial production [10].

In addition to the innovative application of nano-catalysts, the traditional application scope of biotechnology has deeply covered drug research and development (such as gene therapy, monoclonal antibodies), agricultural improvement (such as genetically modified crops, biopesticides), environmental remediation (such as biodegradation, wastewater purification) [11], and industrial manufacturing (such as biological fermentation, enzyme catalysis). This field has always been committed to addressing key challenges such as human health, resource management, and environmental protection, while promoting the development of social productivity towards a greener and more efficient direction [12].

3.1. Nano-catalysts in Medicines

Diseases caused by pathogenic bacterial infections have become a major public health challenge, being the leading cause of human mortality in the early 20th century. The excessive use of antibiotics in recent decades has led to the emergence of multidrug resistance (MDR), a growing crisis that has emerged as a primary global health threat. To protect themselves from bactericidal agents like antibiotics, bacteria often adhere to surfaces and secrete proteins and polysaccharides to form biofilms for self-protection [13]. These biofilms significantly hinder the effectiveness of oral or intravenous antibiotics in eradicating bacterial infections. To address this clinical dilemma, developing robust biocompatible antimicrobial strategies that overcome MDR properties has become crucial [14].

Inspired by catalytic-like activity, there has been growing interest in utilizing various forms and sizes of inorganic nano-catalytic materials for antibacterial applications. These materials stimulate catalytic reactions at pathological sites to generate reactive oxygen species (ROS), which act on bacterial cell membranes to disrupt biofilm structures, increase membrane permeability, and lyse bacteria, providing new approaches for antimicrobial therapy and combating antibiotic resistance. As novel, stable, and highly efficient antibacterial materials with high atomic utilization rates and unrestricted biofilm compatibility, they show potential in wound disinfection. To develop antibacterial nano-catalysts for wound healing, XU et al [15]. Created ZIF-8-derived Zn-N-C catalysts that demonstrated excellent peroxidase-like activity against Pseudomonas aeruginosa, achieving an inhibition rate of up to 99.87% and proving effective as wound treatment agents.

Additionally, due to vigorous bacterial metabolism enriching the microenvironment infection with H_2O_2, HUO et al. developed Fe nano-catalysts (SAF NCs) that efficiently catalyze peroxidase-like reactions. These catalysts generate abundant OH radicals through H_2O_2 catalysis at infection sites, effectively killing both Gram-positive bacteria (Staphylococcus aureus) and Gram-negative bacteria (Escherichia coli) [16]. When combined with localized thermal therapy at bacterial lesions, in vitro antimicrobial assays and in vivo anti-infection experiments confirmed its potent bactericidal efficacy. To tackle the critical MDR challenge, researchers led by Wang have developed a copper-based nano-catalyst that combines hydrogen peroxidase and glutathione peroxidase functions. This photocatalytic therapy targets bacterial infections caused by methicillin-resistant Staphylococcus aureus (MRSA) proliferation in wounds, effectively combating antibiotic resistance while promoting wound healing [17].

3.2. Nano-catalysts in Tumor and Cancer Therapy

Nano-catalytic therapy has emerged as a promising approach in cancer treatment. This innovative strategy enables tumor-specific microenvironment modulation without affecting healthy tissues, generating targeted toxic substances that mitigate adverse effects of conventional therapies while achieving non-invasive therapeutic outcomes. Through systematic investigation of tumor mechanisms, researchers have identified three critical features: 1) vigorous aerobic glycolysis in tumor tissues induces substantial lactate production, causing mild local acidosis (pH 6.0) [18]; 2) superoxide dismutase in the extracellular matrix disproportionate superoxide anions to produce elevated H_2O_2 concentrations (50-100 μmol/L); 3) these inherent tumor characteristics create a unique catalytic environment for chemical reactions. By activating endogenous or exogenous triggers within the tumor microenvironment, this mechanism disrupts cellular redox homeostasis, thereby inducing programmed cell death or necrosis to achieve effective antitumor efficacy [19].

Endogenous triggering mechanisms primarily utilize biochemical substances in the tumor microenvironment, such as hydrogen ions (H^+), hydrogen peroxide (H_2O_2), and glutathione (GSH), to activate Fenton or quasi-Fenton catalytic reactions through single-metal atoms and charge transfer effects in nano-catalysts for tumor cell elimination. The Fenton reaction, mediated by iron ions under acidic conditions, has been extensively studied. Recent research reveals that other metal ions like manganese (Mn^{2+}), copper (Cu^{2+}), and palladium (Pd^{2+}) can also serve as catalytic sites. In the tumor microenvironment's specific weakly acidic environment with H_2O_2 present, these ions trigger quasi-Fenton reactions to generate highly oxidative hydroxyl radicals ($\cdot OH$) and produce additional reactive oxygen species (ROS), which damage cellular DNA strands and effectively eliminate cancer cells. A study by LU et al. reported that copper-doped hollow carbon nanocarbons (Cu-HNCS) exhibit superior Fenton activity in tumors when combined with four-nitrogen-coordinated biomimetic copper catalysts [20]. This system directly catalyzes the decomposition of O_2 and H_2O_2 into ROS (oxygen species O^{2-} and hydroxyl radicals $\cdot OH$) without external energy input, oxidizing intracellular biomolecules to generate potent tumor growth inhibition effects.

3.3. Other Applications

Anti-inflammatory therapy: Under normal physiological conditions, many metabolic processes in cellular life activities generate ROS, and organisms maintain cellular redox homeostasis. However, excessive ROS can lead to pathological processes such as cellular oxidative stress, DNA damage, protein oxidation, and lipid peroxidation, triggering various inflammatory diseases like cardiovascular diseases, inflammatory bowel disease, neurodegenerative disorders, asthma, and arthritis. Therefore, antioxidant therapy is considered a viable approach for treating ROS-related inflammatory diseases. Unlike anticancer and antibacterial mechanisms, anti-inflammatory treatment requires removing excess ROS within cells to restore cellular redox balance. Nano-catalysts with enzymatic characteristics show great potential in protecting oxidative-stressed cells. MA et al. designed nano-dispersed $Fe-N_4$ sites anchored on N-doped porous carbon materials (Fe-SA/NC), which can mimic two antioxidant enzymes-catalase and superoxide dismutase-to eliminate excess

ROS produced by cellular oxidative stress. Additionally, YAN et al. developed an enhanced nano Pt bandage loaded with CeO_2, demonstrating sustained catalytic activity to remove ROS and reactive nitrogen species (RNS) [18]. This significantly improves wound healing in neurotrauma and reduces neural inflammation, thereby protecting neurons.

4. Application of Nano-catalysts in Chemical Technology

In the process of chemical synthesis, nano-catalysts (usually 1-100nm in particle size) have become the key to optimizing reactions in various stages due to their unique surface effects, quantum size effects, and interface effects. In the pre-treatment stage of raw materials(such as refining crude oil after distillation in petrochemicals), their ultra large specific surface area(1 g of nano iron powder has a specific surface area of 100-300m², which is more than 100 times that of micro iron powder)can expose more active sites, efficiently adsorb impurity molecules in the raw materials and catalyze decomposition, thereby improving the purity of the raw materials; When entering the core production reaction (such as ammonia synthesis and fine chemical synthesis), surface effects can significantly reduce the activation energy of the reaction (such as nano iron-based catalysts reducing the activation energy of ammonia synthesis from 335 kJ/mol to below 250 kJ/mol) ,achieving low-temperature and low-pressure reactions, reducing energy consumption, while quantum scale effects can accurately regulate the electronic structure of the catalyst, guide the reaction path in a targeted manner(such as suppressing the generation of by-products in styrene synthesis),and improve the selectivity of the target product; At the same time, its good interface stability can also extend the service life of the catalyst, reduce the frequency of replenishment in production control, and improve the efficiency and economy of chemical synthesis throughout the entire process from raw material processing to product generation [19].The core mechanism lies in chemical reactions where materials undergo oxidation or reduction under specific temperature and pressure conditions. A prime example is the ammonia synthesis process, where nitrogen and hydrogen react to form ammonia underhigh-temperature, high-pressure conditions with iron-based catalysts. Finally, products are refined using techniques like distillation and extraction to remove impurities and meet specifications. This technology is extensively applied in energy sectors (e.g., coal gasification and biomass conversion) and material manufacturing (e.g., synthetic polymer production), providing critical support for energy supply and material preparation [20].

4.1. Nano-catalysts in Hydrogen Production

In the process of hydrogen production, nano-catalyst has become a core material to improve the efficiency of hydrogen production and reduce energy consumption due to its high catalytic activity, excellent selectivity and strong stability. It is widely used in a variety of mainstream hydrogen production technologies.

In the field of water electrolysis for hydrogen production, nano-catalysts can significantly reduce the overpotential in both hydrogen evolution reactions (HER) and oxygen evolution reactions (OER). For instance, platinum-based nano-catalysts such as Pt/C nanoparticles serve as highly efficient HER catalysts. Their nano-scale structure with high specific surface area exposes active sites extensively, substantially boosting hydrogen evolution rates. Meanwhile, non-noble metal nano-catalysts like nickel-iron layered double hydroxide (NiFe-LDH) nanosheets and cobalt-based nano oxides have become preferred materials for water electrolysis anodes due to their low cost and high OER activity, effectively reducing the overall energy consumption of water electrolysis [21].

In photocatalytic hydrogen production, nano-catalysts enhance visible light absorption and facilitate the separation of photogenerated charge carriers. Semiconductor nanomaterials such as titanium dioxide (TiO_2) nanotubes and cadmium sulfide (CdS) nanorods broaden their light-responsive range through size and morphology modulation (e.g., quantum dot formation and heterostructure construction) [22]. When loaded with nano-assist catalysts like platinum and palladium, these materials enable rapid electron transfer and suppress carrier recombination, significantly improving photocatalytic hydrogen production efficiency [23]. These nanomaterials have been widely adopted in solar photocatalytic water splitting for hydrogen generation research.

In fossil fuel reforming processes for hydrogen production (such as methane steam reforming and ethanol reforming), nano-catalysts significantly enhance both reaction rates and product selectivity. Nickel-based catalysts (e.g., Ni/Al_2O_3) and ruthenium-based catalysts demonstrate exceptional catalytic performance in cleaving C-H bonds and facilitating water-gas shift reactions [24]. Their high dispersion effectively reduces coke formation, thereby extending catalyst lifespan. These catalysts play a pivotal role in achieving industrial-scale hydrogen production.

4.2. Other Applicationtions

Beyond hydrogen production in chemical processes, nano-catalysts play a pivotal role across multiple fields. In hydrogen peroxide synthesis, the traditional anthraquinone method remains costly. Recent advancements in low-dimensional NiTe nanoparticles with multidimensional porous structures-rich in grain boundaries, defects, and surface-active sites-have enabled electrochemical green synthesis of hydrogen peroxide. Nickel (Ni) serves as active sites while Te modifications regulate electronic structures, enhancing oxygen adsorption and intermediate binding energy. This provides innovative approaches for efficient production [25]. In organic synthesis, nano-catalysts demonstrate remarkable advantages: Palladium nano-catalysts catalyze hydrogenation reactions between benzene and hydrogen, where their large specific surface area creates numerous active sites, significantly boosting reaction rates compared to conventional palladium catalysts. Zeolite molecular sieve nano-catalysts modulate surface structure and electronic properties, preferentially generating high-molecular-weight polymers during ethylene-propylene copolymerization while improving reaction selectivity [26]. For pollutant degradation, nano-silica and zinc oxide utilize adsorption and catalytic capabilities to efficiently remove organic contaminants like benzene and toluene. Copper nanoparticles catalyze nitration reactions, while silver nanoparticles facilitate hydrogen sulfide reduction, both contributing to environmental remediation.

5. Challenges and Future Perspectives

5.1. Challenges

While significant progress has been made in the application of nano-catalysts across biotechnology and chemical engineering, multiple challenges persist. In biomedical applications, biocompatibility and biosafety remain critical bottlenecks. Most nano-catalysts-such as metal-based nanoparticles-may trigger immune responses or cause organ accumulation during metabolism. For instance, certain nanomaterials entering the bloodstream are prone to macrophage-mediated aggregation, increasing hepatic and renal burdens. Additionally, their stability in complex biological microenvironments is insufficient, making them susceptible to degradation or inactivation by pH changes and proteases, which leads to diminished catalytic performance [27]. Furthermore, targeted delivery efficiency requires improvement, as some materials struggle to reach disease sites precisely, potentially reducing therapeutic efficacy while causing nonspecific damage to healthy tissues. Regarding industrial-scale production and cost control, novel materials like single-atom nano-catalysts require complex fabrication processes demanding high equipment precision, making mass production challenging. Meanwhile, the prohibitive costs of noble metal nano-catalysts such as platinum and ruthenium limit their widespread industrial adoption [28].

In chemical process applications, the recycling and reuse of nano-catalysts pose significant challenges. Particularly in organic synthesis reactions, nanoparticles are prone to deactivation through agglomeration or surface poisoning, while complex separation and recovery processes increase production energy consumption and costs. Moreover, the regulation of catalytic selectivity remains limited. In multi-component reaction systems, precise control over target product formation proves difficult, often accompanied by side reactions that reduce raw material utilization efficiency. Additionally, certain nano-catalysts (such as cadmium sulfide semiconductor materials) exhibit poor chemical stability and susceptibility to oxidation-corrosion [29]. Their performance degradation during prolonged processes like photocatalytic hydrogen production significantly impacts the sustainability of industrial applications [30].

5.2. Future Perspectives

Future research on nano-catalysts should focus on the following directions: In material development, efforts should be intensified to design novel low-toxicity, biocompatible nanomaterials, such as those based on natural biomacromolecules like polysaccharides and proteins, to reduce safety risks in biological applications. The development of high-efficiency non-noble metal nano-catalysts and single-atom catalysts should be prioritized, leveraging atomic-level precision control to enhance catalytic activity and selectivity while reducing costs. Technologically, intelligent design approaches for nano-catalysts should be explored, combining responsive materials (e.g., pH-responsive or light-responsive) to achieve controllable modulation of catalytic performance and improve targeted delivery efficiency. Novel separation and recycling technologies, including magneto responsive nano-catalysts and biodegradable nano-catalysts, should be developed to address recycling challenges. Across disciplines, integration of nano-catalysis with cutting-edge technologies like gene editing and artificial intelligence is crucial. AI-assisted design optimization of nano-catalyst structures and properties will accelerate their application in precision medicine, green chemistry, and related fields.

6. Conclusion

This paper systematically reviews the current applications of nano-catalysts in biotechnology and chemical processes. The results demonstrate that nano-catalysts, leveraging advantages such as size effects, high specific surface area, and surface modifiability, have achieved breakthroughs in biomedical non-oncological treatments (e.g., antimicrobial therapy, anti-inflammatory applications, neurodegenerative disease intervention) and biosensing. They address issues like poor stability of traditional enzyme preparations and insufficient targeting capability of chemical catalysts. In chemical processes, they significantly enhance hydrogen production efficiency through water electrolysis, photocatalysis, and fossil fuel reforming technologies, while exhibiting efficient catalytic performance in hydrogen peroxide synthesis, organic synthesis, and pollutant degradation. Additionally, the development of novel materials like single-atom nano-catalysts and composite nano-catalysts further integrates multi-component advantages, driving upgrades in catalytic performance. However, limitations in biocompatibility, large-scale production, recycling, and selective control remain, constraining their industrial application progress. Biotechnology is related to human health and ecological restoration, while the chemical industry serves as the core of energy conversion and material synthesis [31]. Both fields are limited by traditional catalytic systems: in biotechnology, natural enzymes are prone to inactivation and chemical catalysts have poor targeting, while the chemical industry faces issues such as low reaction efficiency and heavy pollution [32]. Nano-catalysts, due to their high specific surface area, abundant active sites, and modifiable surfaces brought by the size of 1-100nm, can solve the problems in both fields simultaneously, thus becoming a research focus. In biotechnology, they can catalyze the production of reactive oxygen species for antibacterial purposes and scavenge free radicals for anti-inflammatory effects, as well as achieve precise drug delivery. In the chemical industry, they can reduce the overpotential of hydrogen production by water electrolysis, improve the efficiency of photocatalytic hydrogen production, and optimize the selectivity of organic synthesis.

Currently, research and development are underway on single-atom and composite nano-catalysts to improve their biocompatibility and recyclability, thereby promoting the efficient and green development of both fields.

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