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REVIEW PAPER

Nanozymes as Catalytic Marvels for Biomedical and Environmental Concerns: A Chemical Engineering Approach

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Abstract

Nanozymes, a class of nanomaterials endowed with enzyme-like catalytic activities, have emerged as a transformative force in the fields of biotechnology and environmental science. This review provides an in-depth analysis of nanozymes, from their synthesis and properties to their diverse applications. The synthesis of nanozymes is a pivotal aspect of their development, involving intricate methods to create these nanoscale catalysts. The exploration begins with a fundamental definition of nanozymes as nanomaterials mimicking the catalytic functions of natural enzymes. Then the paper delved into numerous sources of nanozymes, ranging from noble metals to metal oxides, and elucidates the key preparation techniques that enable the fine-tuning of their catalytic properties. The remarkable properties of nanozymes are closely examined, focusing on their catalytic efficiency, stability, and adaptability. These properties lay the foundation for the extensive array of applications they offer. Nanozymes have revolutionized the imaging and tracking of microbes through luminescence and fluorescence detection, making them invaluable in understanding and combatting bacterial and viral infections. Their integration into biosensors has elevated disease detection and pesticide monitoring to unprecedented levels of sensitivity and accuracy, promising innovative solutions for diagnostic and analytical purposes. Additionally, nanozymes have paved the way for advancements in immunoassays, enhancing the precision of disease diagnosis and therapeutic interventions. Furthermore, the therapeutic potential of nanozymes is gaining recognition, with notable applications in antibacterial, antioxidant, and antifouling treatments. Their use in the treatment of cardiovascular diseases, cancer therapy, and orthopaedics showcases their versatility in clinical applications. In the food industry, nanozymes have improved food quality, safety, and shelf life, contributing to our well-being. Moreover, nanozymes have demonstrated their environmental significance by efficiently detecting and degrading pollutants, thereby promoting water treatment and environmental preservation. In summary, this review encapsulates the dynamic landscape of nanozymes, providing a technical insight into their synthesis, diverse properties, and wide-ranging applications. Nanozymes, with their unparalleled versatility, hold great promise for addressing contemporary challenges in both biotechnology and environmental sustainability.

Keywords Nanozymes · Bioimaging · Mimicking · Food Industry · Pollution Detection · Waste Water Treatment

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Introduction

The field of nanotechnology has the potential to bring in change to a number of industries, including medicine, diagnostics, environmental monitoring, and food safety. The Nobel Laureate Richard Feynman pioneered nanotechnology knowledge in his famous speech at the California Institute of Technology on December 29, 1959 [1]. Nanoparticles (NPs) are now manufactured utilizing a variety of processes, including physical, chemical, and biological methods. Nanozymes have the benefits of simple synthesis, low cost, and great stability while also demonstrating excellent catalytic activity with tunability and eliminating the flaw of natural enzymes [2]. Higher energy, inert gases, and a greater area for instrument implementation are used in physical approaches. The synthesis of NPs is expensive and uses a lot of radiation [1]. These artificial nanostructures have intrinsic catalytic activity similar to that of natural enzymes, making them a promising approach for tackling difficult problems in a variety of fields. Nanozymes have various catalytic processes that act as enzyme mimics, such as peroxidase, oxidase, glucose oxidase, and others, and can be used as labels in the development of immunoassays to achieve high detection sensitivity and selectivity [3, 4]. Due to their ability to replicate enzymes and diverse range of uses, nanozymes are one of the most astounding advancements in nanotechnology.

Nanozymes have generated a great deal of interest since they are less expensive, more durable, and physiochemical stable than natural enzymes in hostile settings [5]. Since the metallic active core can successfully replicate the catalytic electronic redox process enabled by natural enzymes, nanozymes are now mostly made of metal and metal oxides. It's intriguing how the characteristics of a disease differ from normal tissues and offer typical therapeutic alternatives for the logical design and use of nanozymes in biomedicine [6]. The tumor microenvironment (TME) is widely recognized to have higher redox potential values than normal tissues. These tumor-specific properties can facilitate the nanozymes' ability to operate like enzymes [7, 8]. Despite the widespread use of nanozymes in biomedicine, it is still difficult to gain an elementary comprehension of the critical elements that influence the catalytic efficiency, enzymatic-like features, and substrate selectivity of nanozymes based on the interaction between intrinsic structure and extrinsic environment [9].

Recently, a wide range of biomedical applications for various types of nanozymes have been reported, including oxygen-dependent tumor therapy, radiotherapy, chemodynamic therapy, bacterial infection diseases, and diseases linked to Reactive Oxygen Species (ROS), among others [10–12]. Therefore, recent advances in the application of nanozymes in the biomedical sector may offer new insights on the spread of nanoparticles in the biomedical sector [6]. The use of nanozymes in therapeutic applications has opened up new avenues for the identification, treatment, and administration of targeted drugs. These nanoparticles' enzymatic activity makes them effective catalysts for a variety of biological processes. Gold-based nanozymes have been used for targeted medication release in cancer therapy, taking advantage of their special features to cause controlled dispensing of therapeutic drugs in response to particular stimuli [13]. Infectious disease diagnosis is greatly aided by the development of nanozymes as effective instruments for imaging and detecting microbial infections.

Nanozymes can play a pivotal role in colorimetric or fluorescence assays by using their catalytic activity, enabling quick and accurate pathogen detection. The promise for early disease diagnosis is demonstrated by Lin et al. 2017[14], which guides us how to use nanozymes for pathogenic bacterial detection by colorimetric assays. The multidisciplinary nature of research on the application of nanozymes in detection and recognition of pathogens necessitates chemists and physicists for nanozyme designing, fabrication, and characterization; microbiologists for methodology design, testing, and analysis; and clinicians or clinical researchers for clinical evaluation of the methodologies and devices [15].

Nanozymes have sparked a revolution in biosensing technology by providing approaches that are more sensitive and selective than traditional ones. These nanoparticles have been incorporated into platforms for biosensors that can detect poisons, pollutants, and biomolecules. Nanozymes have the potential to completely transform point-of-care diagnostics, as demonstrated by Niu et al. [16] that emphasizes the creation of a nanozyme-based biosensor to identify glucose. Nanozymes can be used to combat pollution and contamination problems and also to protect the environment. Nanozymes are capable of catalyzing degradation processes, which aid in the detoxification of contaminants in soil and water. One promising method for long-term environmental restoration involves iron-based nanozymes, which have been used to remove organic pollutants [3].

The materials that make up nanozymes are a wide variety, each with unique catalytic properties. These include nanozymes based on metals (such as gold, silver, and iron), nanozymes based on metal oxides (such as manganese oxide, cerium oxide), and nanozymes based on carbon (such as graphene, carbon nanotubes). Depending on the desired catalytic activity and intended use, a particular type of nanozyme is selected. We set out on a tour through the intriguing world of nanozymes and their varied uses in this extensive review. The creation of novel, effective artificial enzymes has received a lot of attention in the present. In the beginning, scientists focused on cyclodextrins, porphyrins, polymers, and supramolecules that resembled the structures and catalytic functions of enzymes [4].

Nanozymes and its Synthesis

Nanozymes also referred to as "enzyme mimics" [17], are utilized in a wide range of applications, they also consist limited stability and is expensive due to the use of technologically developed strategies that are complex, thus nanozymes are considered to be advantageous as they are prepared using simple technological strategies possessing greater availability for usage [18].

Nanozymes have been classified into various enzyme-based nanomaterials (Fig. 1) and are commonly used in various fields for testing, therapies, biosensing and so on [19]. Preparation of nanozymes was done on the basis of different methods such as hydrothermal, solvothermal, co-precipitation, sol-gel and other methods that also depict its enzyme activities [20].

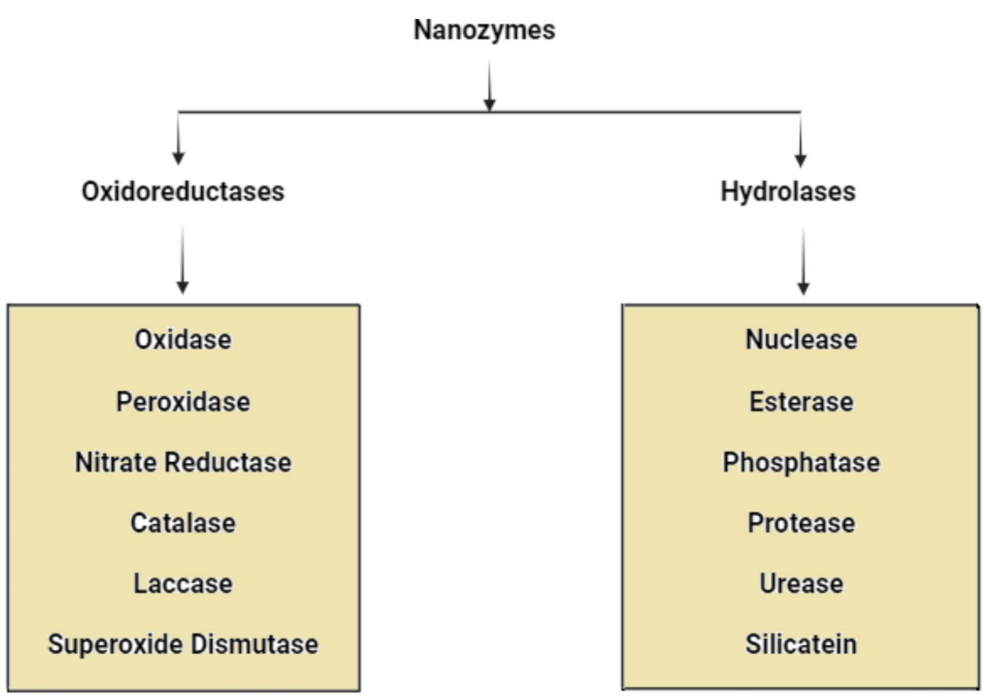
Recent Applications of Nanozymes

Nanozymes have recently been used in biosensing, targeted drug delivery, cancer therapy, environmental cleanup (viz. water purification and air pollution management), and even disease diagnosis (Fig. 2). Because of their stability, controllable catalytic activity, and compatibility with biological systems, nanozymes are attractive tools in a variety of domains. Nanozyme systems have successfully replaced traditional enzymes for catalysis by either imitating the catalytic sites of natural enzymes or by housing multivalent components for reactions [21]. Tables 1 and 2 depicts the specific properties of oxidoreductase nanozymes.

In-depth study has recently concentrated on creating diverse nanozyme systems that are responsive to one or more substrates in a targeted manner. The pH, H_2O_2, glutathione, and oxygenation levels in various microenvironments can all affect how catalytically active nanozymes [21]. It is anticipated that stimuli-responsive nanozymes will open up new possibilities for diagnosis, treatment, and theranostics by merging the catalytic property and inherent nanomaterial nature of nanozyme systems [21]. On diverse nanoscale substrates for catalytic processes, essential functional groups are cooperatively anchored. Later, multivalent element-homing nanozymes (for example, those that can target metal ions or carbon atoms) were developed, and they are now finding more and more use in the healthcare industry. Most single-substrate nanozymes have a Michaelis-Menten catalytic kinetic profile, whereby differentiates the catalysis into binding and reaction phases [21].

The physical characteristics, symptoms, and specific disease-related marker molecules of the patient are used in clinical diagnosis to deduce and determine the pathophysiology and potential causes [22]. Enzyme-based assays have emerged and become more common for identifying disease-related marker molecules and clinical diagnosis as a result of our expanding understanding of enzymes and the development of several observable substrates [22]. The high stability of nanozymes makes it easier to detect target

Fig. 1 Types of Nanozymes



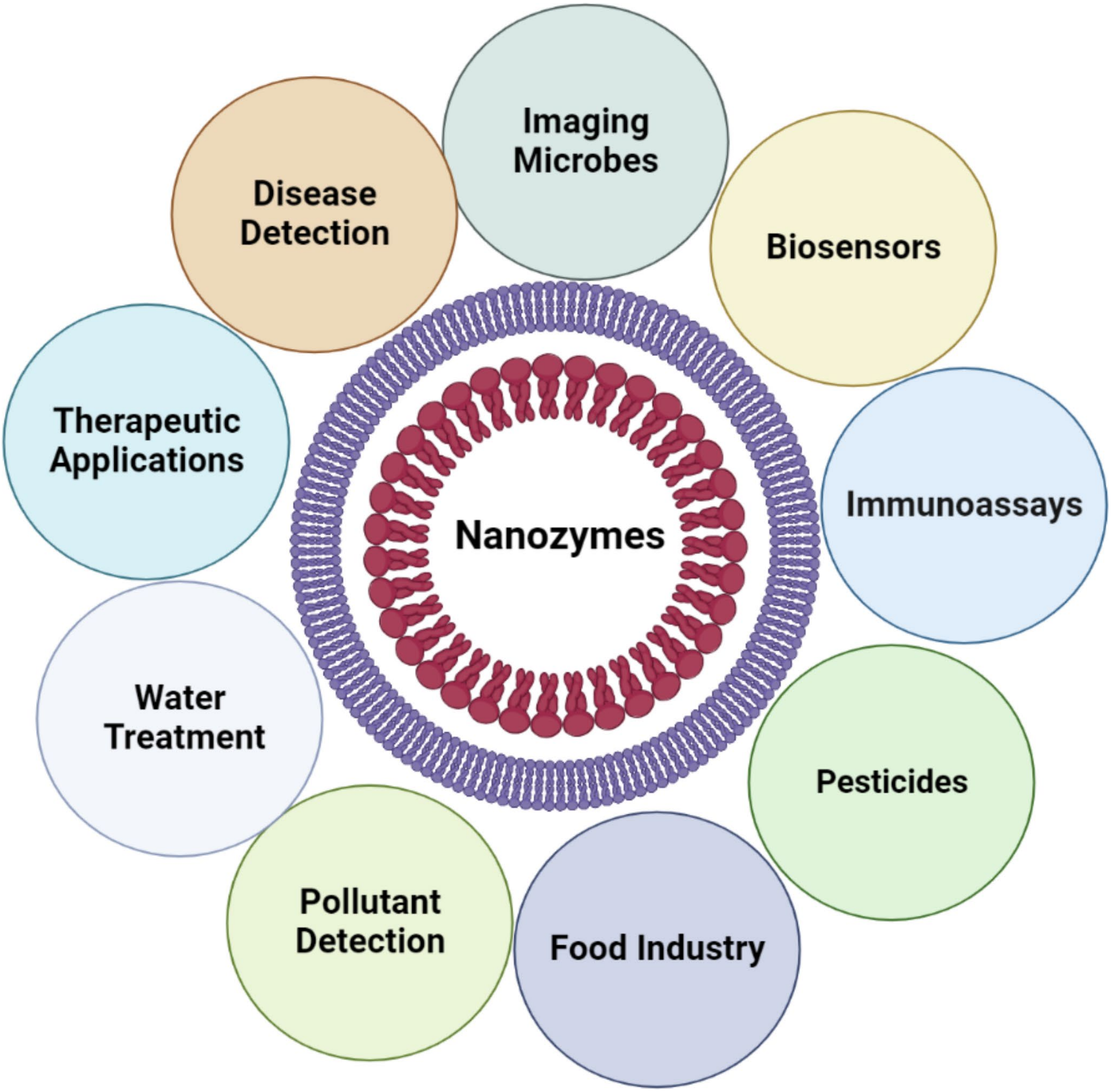


Fig. 2 Various applications of nanozymes in different areas ranging from imaging microbes to pollutant detection

objects in challenging environments while successfully preventing denaturation and inactivation. Natural enzymes face issues with instability and high application costs despite the promise that enzyme-linked assays hold in the detection of environmental pollutants and disease-related indicators. The detection of biomarkers and environmental toxins has showed significant promise for nanozyme. Nanozymes have highly changeable activity thanks to the complex compositions and nanostructure characteristics of nanomaterials such as size, shape, crystal plane, surface modification, hybridization, and heteroatom doping [22].

For instance, Fe_3O_4 magnetic nanoparticles can perform the dual roles of peroxidase nanozyme probe and magnetic separation reagents to achieve the function of separation and detection, improving the sensitivity of the test strip detection [22].The detection is facilitated by many enzyme-like functions of nanozyme. For enzyme processes, peroxidase-like NPs have been created to identify active substances like glucose, dopamine, xanthine, glutathione, adenosine triphosphate, metal ions, and enzyme inhibitors [23].

Recent years have witnessed an increase in interest in photoelectrochemical (PEC) sensors based on catalytic

Table 1 List of specific oxidoreductase nanozymes and their properties

Type of Nanozyme	Source	Key Preparation Method	Enzyme like Properties	Applications	References
Cu, CuO based nanozymes	Synthesis of hollow carbon spheres	Carbonization method of source, NaOH and EDTA treatment of copper ions	Peroxidase	Biosensing, wound healing, tumors, acute kidney injuries	[21, 22]
Fe_3O_4 based nanozymes	Synthesis of natural occurring mineral magnetite	Co-precipitation, solvothermal and thermal method of synthesis	Peroxidase	H_2O_2 detection, biosafety detection such as cancer markers and pesticides	[23]
GO based nanozymes	Oxidative product from graphite	Synthesized using Hummer's method using Graphite flakes	Peroxidase	Glucose detection, Colorimetric detection of specific antigens in cancer biomarkers	[24, 25]
Mn_3O_4 based nanozymes	Oxidative product of Mn+	Synthesized by hydrothermal method	Catalase	H_2O_2elimination	[26]
CH-Cu nanozymes	Natural laccase compound	Electron Transfer pathway of Cu^+ with Cys-Histidine dipeptide	Laccase	Detection of toxic phenolic contaminants, Detection of epinephrin	[27]
CdS-Pt	Metal-based composite material	Chemical reduction of metal ions using ascorbic acid	Nitrate Reductase	Selenite detection in mineral water, Photocatalytic Hydrogen evaluation	[28]
CeO_2 based nanozymes	Surface Environments	Synthesized by highly reversible redox reactions using Ce^{3+}/Ce^{4+} catalysts	Superoxide dismutase (SOD)	Diagnosis and treatment of Parkinson's disease, tumor and inflammation therapies	[29]

Table 2 List of specific hydrolase nanozymes and their properties

Type of Nanozyme	Source	Key Preparation Method	Enzyme like Properties	Applications	Reference
ZIF-8 nanozyme	Hydrophobic amino acid	(Zn^{2+}) + 2-mIM in the presence of AA gives ZIF-8	Esterase	Quantifying and detecting the presence of sulfonamides in cow milk	[30]
ZrO_2 NPs Based nanozymes	Zr element present as heavy minerals on earth surfaces	Co-precipitation method using zirconium chloride and NaOH as precipitant	Phosphatase	Chemo/biosensing, detection of methyl parathion,	[31]
Cu-MOF	Prepared using chemicals and reagents	Protein solution preparation method using copper (II)	Protease	Hydrolysis of casein and used for trypsinization in cell cultures	[32]
fullerene (C_{60}-$_1$and $C_{60\text{-}2}$) based nanozymes	Derivatives of carbon-based nanomaterials	Composed of 60 carbon atoms and is synthesized to a water-soluble nanomaterial	Nuclease	Cleaving to the DNA, specific binding properties	[33]
AuNPs based nanozymes	Reduction reactions of Au ions and using green biosynthesis method	Collection of plant extracts that contain certain chemicals having the ability to reduce metal ions to metal elements	Silicatein	Used to design biosensors and apt sensors	[34, 35]

precipitation caused by peroxidase nanozymes. Antibiotic misuse and haphazard disposal, such as with chloramphenicol (CAP), contribute to major issues like bacterial resistance and damage to the environment [22]. Since a single substrate can provide a variety of signals and nanozymes can simultaneously elicit several responses, it is possible to combine a variety of signals for multimodal detection to deliver more accurate and comprehensive information [22]. Nanozymes are a subfield of nanomedicine in the bio-medical sciences.

Nanozymes provide more functions than enzymes for analytical applications. Engineered nanozymes also have magnetic force, surface plasmon resonance, and photothermal activity in addition to catalytic activities provided by metal active sites [24].Additionally, nanozymes can be employed for pathogen inactivation, wound healing, and biosensing. They are a promising field for research and development due to their adaptability and potential in medicinal therapies. The capacity of nanozymes to scavenge Reactive Oxygen Species (ROS) is mostly a result of their ability to mimic Super Oxide Dismutase (SOD), which reduces intracellular ROS levels and improves cell viability by converting superoxide into $H_2O_2$and then O_2 and H_2O [23].

Bioconjugation is a difficult task among these applications. Nanozymes must be attached to affinity ligands in order to be used in biological applications such target medication delivery, biosensing, and bioimaging. High peroxidase-like metal NPs have been produced using proteins as templates. Similar to this, researchers have been able to create unique nanozymes with DNA metallization thanks to DNA's extensive physiochemical characteristics [23]. These nanozymes exhibit remarkable specificity and efficiency when used as colorimetric reporters. In vivo organ/cell sensing is crucial in biomedical imaging. In the presence of hydrogen peroxide, iron oxide NPs can accelerate the oxidation of peroxidase substrates, resulting in a color response like to that of natural peroxidases [23]. Other treatments often include three aspects: tissue oxygen, light/US, and a photo/radiation/sonosensitizer. To manage the tumor microenvironment for combination therapy, photosensitizer and nanozymes can be used. This increases the therapeutic efficacy of photodynamic therapy (PDT) and sonodynamic therapy (SDT). This is due to the fact that some nanozymes can trigger the breakdown of endogenous H_2O_2as catalase in the tumor microenvironment to produce O_2 and attenuate hypoxia while enhancing radiation response.

In the field of research, concerns about bacterial resistance are increasing tremendously. Platinum nanoparticles PtNPs' lower zeta potential may cause membrane and cell wall rupture, which would then cause the release of intracellular content. Gram positive and Gram-negative bacteria were found to be harmful to pectin-capped PtNPs (2–5 nm) both *in-vitro* and *in-vivo*. Environmental scientists have long struggled with the difficulties of pollution detection and degradation. Since nanozymes catalyze H_2O_2 to produce OH, which attacks organic compounds and produces intermediate species before converting to CO_2 and H_2O, nanozyme-based methods have been shown to be straightforward yet effective for the detection and degradation of pollutants like dyes (methylene blue, rhodamine), lignin, and other organic compounds (phenol, benzene, anilines, chlorophenols, melamine), which are present in wastes and food [23].

Additionally, nanozymes in the energy sector may contribute to the generation and storage of renewable energy sources, such as by catalyzing reactions in fuel cells. As research advances, it is probable that these adaptable nanostructures will be used in novel ways to advance technology and enhance a number of facets of our lives.

Nanozymes in Imaging Microbes

Nanozymeshave emerged as powerful tools in various biomedical applications, including disease diagnosis, therapy, and imaging [25]. One of the fastest expanding applications of nanotechnology today is the detection of infections and the diagnosis of diseases caused by them, known as nanozymology, which is a new term for the science of nanozymes [26]. In recent years, their unique catalytic properties have been harnessed for the detection and visualization of microbes, revolutionizing the field of microbiology and disease research. Conventional microbial imaging techniques often rely on fluorescent labels or radioactive probes, which can have limitations in terms of sensitivity, specificity, and potential toxicity [27]. Nanozyme-based imaging, on the other hand, offers a promising alternative, leveraging the catalytic activity of nanomaterials to generate highly specific and sensitive signals for microbial detection.

Luminescence and Fluorescence Detection

Nanozymes have become a flexible platform for a range of biomedical use [25]. Luminescence and fluorescence detection methods have transformed the study of nanozymes in the imaging of microorganisms, providing strong and receptive instruments for microbial detection and visualization. Incorporating luminous and fluorescent probes with nanozymes has been made possible by the special catalytic features of these enzymes, the result is hybrid nanostructures that amplify and provide highly targeted signals for microbial imaging.

Metal nano-clusters (NCs) are a class of potential fluorescent nanomaterials that have attracted a lot of interest in catalysis, sensing, and bioimaging applications because of their distinctive sub-nanometer dimensions, controllable fluorescence emission, and outstanding biocompatibility [28, 29]. Numerous fluorescent NCs have been created and synthesized thus far. Due to the unique interactions between the sensor and the analyte, fluorescent sensors often respond to the analyte with augmented or quenched fluorescence intensity. Additionally, the metal-metal and metal-ligand bonding properties of these NCs allow for fine-tuning of their size, structure, and composition [30, 31]. Due to their ease of use and high sensitivity, fluorescent sensors have attracted growing interest for biosensing and cell imaging.

A fluorescent sensor's "turn-on" switch has a higher signal-to-noise ratio than its "turn-off" switch, in comparison [32]. The detection signal resulting from the change in intensity at one emission wavelength is typically problematic due to inevitable interferences from analyte-independent factors, such as environmental fluctuations, instrumental efficiency, local concentration variation of sensors, and the sample matrix. Another fluorescence signal is added to the ratiometric sensors' design to get around this problem. As a result, these sensors have at least two emission wavelengths where they are differently sensitive to the target. After then, the emission intensity ratios are calibrated to show how the target concentration has changed. Ratiometric fluorescence techniques, like other self-calibration analytical techniques, can increase signal-to-noise ratios while also enabling precise molecule identification and imaging [33, 34].

Typically, bottom-up, top-down, or a mix of bottom-up and top-down nanomaterial preparation, followed by surface-chemistry modification, is the first step in the construction of ratiometric fluorescent bionanosensors. The nanomaterial-based ratiometric biosensors' crystal structure, chemical make-up, shape, size, and surface characteristics all contribute significantly to their outstanding performance in fluorescence sensing and cell imaging applications to detect changes in target concentration. Ratiometric fluorescence techniques, like other self-calibration analytical techniques, can increase signal-to-noise ratios while also enabling precise molecule identification and imaging [35]. The reference signal and the analyte-sensitive signal come from separate probes. The latter makes it possible to normalize the former. Basically, physical mixing of the two probes is a simple method to produce this ratiometric biosensing or cell imaging. However, the procedures may become challenging due to the demand for two independent probes.

For instance, if these two probes are distributed unevenly within cells, misleading imaging results may be obtained. Dual-emission single nanoprobes have the advantage of eradicating mistakes caused by changes in probe concentration, in order to generate dual-emission signals from a single nanoprobe, preconjugation or preassembly is required. Chemical or physical techniques can be employed to accomplish this. This design method increases the single nanoprobes' dependability, encouraging their use in biosensing and other fields [36]. Nanozyme-based microbe imaging has been transformed by luminescence and fluorescence detection techniques, which provide reliable instruments for microbial identification and visualization.

Nanozymes offer a versatile platform for biological applications since they have the ability to mimic enzymes naturally. Hybrid nanostructures are made by combining bright and fluorescent probes, and they offer highly focused signals for accurate microbiological imaging. For sensing and bioimaging, metal nanoclusters (NCs) with controlled fluorescence emission and biocompatibility have generated interest. Accurate microbiological imaging and improved signal-to-noise ratios are made possible by ratiometric fluorescent techniques. Errors brought on by variations in probe concentration are eliminated by dual-emission single nanoprobes.

Bacteria

Researchers have been captivated by microorganisms, particularly bacteria, because of the crucial roles they play in ecosystems, human health, and illness [37]. Considering infectious diseases account for a large proportion of hospitalizations and deaths worldwide, there has been considerable interest in the use of nanoparticles in the diagnosis of communicable diseases [38, 39]. Innovative methods are required to comprehend their complex behaviour. Nanozymes have become revolutionary tools for microbial imaging, particularly in the visualization and study of bacteria. Pathogen detection and identification biosensors vary in complexity, sensitivity, reaction time, cost, reliability, and durability, which are considered to be among the most desirable indications. The use of nanozymes in biosensor processes can significantly increase the performance of various pathogen biosensor devices [37, 40, 41]. Nanozymes can be used to detect pathogens directly through mechanisms that include nanozyme interaction with the pathogen, or indirectly through mechanisms that involve nanozyme interaction with chemical compounds produced by the pathogen [15].The nanozyme redox current is inhibited by *Yersinia enterecolitica* immobilized on the electrode, which causes the detection signal to be inversely proportional to the amount of bacterial analyte present in the sample. Figure 3 illustrates how to prepare the working electrode [42].

A recent report on a sensor based on polymer nanospheres ornamented with platinum quantum dots that uses the sandwich immunoassay strategy provides an example of a nanozyme-based technology that holds great promise for improving the direct detection and identification of *Salmonella typhimurium* with high sensitivity [43]. The influence of revolutionary nanozyme-based technologies on the detection and identification of disease-causing pathogens is faster detection time, lower detection limits, cost-effective detection, concentration dependant outcomes, and quality devices, which will increase point-of-care usage. Along with the advancement of nanozyme-based diagnostics, various revolutionary nanozyme-based therapeutic technologies are already improving treatment strategy options in the clinic [44].

Virus

Viruses are composed of a capsid protein or lipid-protein complex encapsulating nucleic material in various shapes and two main kinds [15]. Nanozymes are currently a fast-growing area of study in the field of nanobiotechnology, and their uses in bioanalysis, bioimaging, and biomedicine have all been thoroughly investigated. In contrast to natural enzymes, the fundamental advantage of nanozymes is that

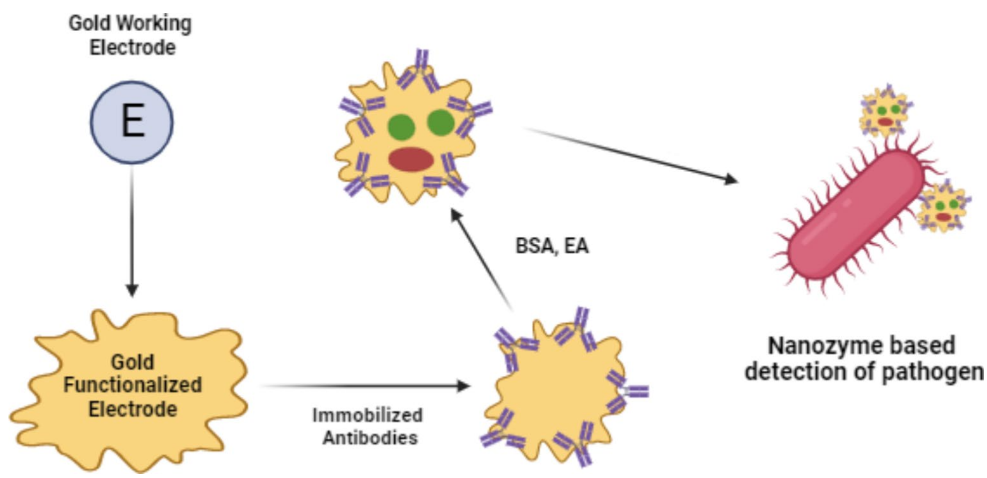


Fig. 3 Schematic representation of interaction of gold functionalised electrode in *Yersenia enterecolitica* detection

their activity can be modified by varying their size, shape, dopant content, and surface properties [45, 46]. The invention of a low-cost, field-portable sensor based on colorimetric detection of infectious virus infections allows for the identification of target analytes at an extremely early stage in complicated biological matrices [47, 48]. Incubation and growth, immunoassays, and polymerase chain reaction (PCR) techniques are three methodologic milestones in the progress of pathogen detection and identification [15].

Nanozymes Based Biosensors

A breakthrough fusion of nanotechnology and biomedicine, enzyme-based biosensors has the potential to revolutionize pesticide monitoring, disease detection, and diagnostics. Nanozymes in diagnostics provide ultra-sensitive and quick detection of disease biomarkers, paving the way for early disease diagnosis and personalized therapy. They offer a quick and accurate way to recognize pathogens, viruses, and bacteria for disease detection, supporting healthcare interventions during epidemics [49, 50].

Nanozymes provide an environmentally benign method to identify pesticide residues in soil, water, and food items, ensuring sustainable practices and food safety in the fields of agriculture and environmental protection [51]. Nanozyme-based biosensors have the potential to completely transform a variety of industries, opening the path for improved healthcare and environmental preservation [52].

Diagnostics and Disease Detection

Nanozymes-based biosensors have become an innovative technology with game-changing uses in disease detection and diagnosis. Attributed to their catalytic capabilities, it is possible to selectively and effectively identify infections and disease biomarkers at extremely low concentrations. Nanozyme-based biosensors make use of their excellent sensitivity and specificity to provide a quick and accurate way to identify diseases in their early stages, enabling better results for patients through prompt treatment and personalized therapy [53].

The multicomponent transition metal dicalchogenide TMD (MCFs/rGO based nanozyme was also effective in measuring the concentration of various biologically important analytes [53]. The MCFs/rGO is one of many existing and upcoming multicomponent TMD-based nanozymes that could open the door to a large arena of applications yet to be explored [53]. In answer to this need, a new lateral flow plasmonic biosensor has been developed that employs gold-viral bio mineralized nanozymes for on-site intracellular glutathione detection[54].Glutathione, a critical cellular antioxidant and biomarker, is important in drug resistance processes. The proposed nanozyme-based biosensor has high sensitivity and specificity, allowing for rapid and precise assessment of intracellular glutathione levels in patient samples. By utilizing the unique catalytic properties of nanozymes, this biosensor provides a promising avenue for early detection of drug-resistant infections, allowing healthcare professionals to make informed decisions and tailor personalized treatment regimens for improved patient outcomes [55].

Core-shell nanozymes paired with oxidase enzyme biosensors have developed as a game-changing device for noninvasively monitoring diabetes and hypoxia simultaneously. These nanozyme-based biosensors have unique catalytic properties that allow for sensitive and selective detection of proteins linked to both conditions. By combining these tasks into a single diagnostic tool, healthcare professionals may easily monitor both glucose levels and tissue oxygenation in real time without intrusive procedures [56].

Nanozymes have showed considerable promise in tumour therapy mediated by reactive oxygen species (ROS) [57].However, the tumour microenvironment is highly complicated, resulting in insufficient catalytic efficiency of nanozymes, and hence the essential therapeutic benefits are rarely realized. Another prospective technique for effective tumour catalytic therapy is to increase the catalytic activity of nanozymes[58]. The single nanozyme-based catalytic therapy is typically less successful and capable than combinational therapy due to the low concentration of H_2O_2 in the tumour microenvironment. Nanozymes also have the potential to treat tumours by mediating ROS, and research is now being done on catalytic activity enhancement and phototherapy-assisted combination therapy [57]. Recent advances in phototherapy, in particular the use of near-infrared lasers, have demonstrated an improvement in the catalytic activity and, subsequently, the therapeutic efficacy of nanozymes [59].The catalytic activities of nanozymes are mainly attributed to their unique surface properties and composition. The two primary catalytic activities demonstrated by nanozymes are peroxidase-like activity and oxidase-like activity. These activities enable nanozymes to catalyse the conversion of substrates into products, generating detectable signals that are utilized for biosensing [60]. High sensitivity and specificity nanozyme-based biosensors are available for individualized treatment and the early diagnosis of disease.Despite obstacles, continued developments ensure that nanozyme-based biosensors will be essential for enhancing global healthcare and disease management.

Pesticides

The creation of cutting-edge technologies to detect and reduce pesticide contamination has elevated to a top priority on a global scale due to growing environmental concerns and the requirement for sustainable practices[61]. A ground-breaking solution with the potential to revolutionize pesticide detection and environmental preservation has emerged: nanozymes-based biosensors. These sensors are at the cutting edge of nanotechnology and biomedicine. These nanomaterials provide a strong and adaptable platform for the quick, sensitive, and targeted detection of pesticides in a variety of environmental matrices because they are endowed with catalytic activities that mimic those of enzymes [51].

However, the majority of conventional biosensors are built using bio-recognition components, such as biological enzymes, which are pricy, unstable, and unsuitable for the field detection of changeable surroundings [62]. Due to their exceptional qualities, nanomaterials have created new opportunities for the widespread application and commercialization of biosensors with the advancement of nanotechnology [63].

Many nanozyme-based biosensors have been developed and used in recent years for the analysis of organophosphorous pesticide (OP) residues. These nanozymes can be broadly categorized as metal-based, metal-oxide-based, carbon-based, and metal-organic framework (MOF)-based nanozymes depending on the types of materials used. They mimicoxidoreductase and hydrolase activity [62, 63] are employed for OP detection. Ananozyme-based biosensor's sensing methods, such as a single nanozyme and its integration with other bio-recognition components like an enzyme, an antibody, and an aptamer. Application of nanozyme-based biosensors, such as portable and on-site equipment and optical (e.g., colorimetric, fluorescence, chemiluminescence, and surface-enhanced Raman scattering) and electrochemical biosensors [64]. The most popular biosensors for OP detection, optical sensors are unquestionably quick, easy, and inexpensive an optical sensor typically consists of two components: an identifier that specifically interacts with the detection target and a transducer that transforms the outcome into a signal output [61].

Acetylcholinesterase (AChE) is a naturally occurring enzyme that encourages the breakdown of the neurotransmitter acetylcholine to produce choline and acetate. It has been investigated as a straightforward method to identify pesticides since some pesticides can affect the AChE activity. The fact that AChE is one of the numerous enzymes that pesticides can inhibit must be noted, though. For instance, choline oxidase, peroxidase, and butyrylcholinesterase can all be inhibited by organophosphorus pesticides (OPPs), but tyrosinase can be blocked by diazinon and carbaryl [65]. The most frequent indicator of pesticide contamination in the literature to date is the inhibition of AChE. In this situation, it has been discovered that OPPs permanently inhibit AChE activity, but carbamates only temporarily inhibit the enzyme before it gradually resumes its activity. It's interesting to note that the only two pesticides known to interact with AChE are OPPs and carbamates. Because of this, AChE is a good marker to identify OPPs and carbamates. Acetylthiocholine, one of the substrates for the AChE enzyme, is changed into thiocholine by the enzyme.

Thiocholine, a potent reducing agent, has the potential to either block or reoxidize the colorimetric product of a nanozyme-catalyzed process, resulting in less colour generation, using an oxidasemimic cerium oxide nanozyme, this method produced detection limits for dichlorvos and methyl paraoxon of 8.62 ppb and 26.73 ppb, respectively [66, 67]. The shrinking of portable and handheld devices for real-time monitoring, which enables point-of-care applications for non-expert users in agricultural contexts, is one of the future approaches in nanozyme-based biosensors for pesticide detection. Additionally, strong, wireless field deployable technology will allow for remote pesticide screening.

Environmental monitoring will broaden the application's use beyond agricultural products, while multianalyte detection, intelligent sensing, and automation will increase efficiency and accuracy. Reliable quantification and toxicity evaluation will be made possible by integration with bioinformatics and data analytics. Widespread acceptance will be ensured through standardization and governmental clearances, which will eventually result in safer and more sustainable agricultural practices and environmental protection [51]. The development of biosensors based on nanozymes has the potential to revolutionize the detection of pesticides and address environmental issues. These nanoparticles enable quick and accurate pesticide detection in many environmental matrices thanks to their catalytic activities that imitate enzymes.

Nanozymes in Immunoassays

Nanozymes have become an important resource for refining and improving diagnostic procedures in the field of immunoassays. Nanozymes have been used in place of natural enzymes to create modified immunoassays that are more sensitive and stable than conventional enzyme-immunoassays. These nanozymes can act as signal amplification catalysts in immunoassays by simulating the catalytic properties of natural enzymes like peroxidases or oxidases. The advantages of nanozyme-based immunoassays include lower background noise, higher signal-to-noise ratios, and higher detection limits. Due to its advantages of high specificity and sensitivity, immunoassay has received significant interest as a quick and easy approach for the detection of numerous targets. Notably, the widely used immunoassay known as the enzyme-linked immunosorbent test (ELISA) can offer excellent detection sensitivity because the enzyme labels can encourage the production of catalytically amplified readouts.

Natural enzyme labels, however, typically suffer from poor stability, high cost, and challenging storage [68]. These advantages help to produce more precise and trustworthy results, which make them very useful in pathogen identification, biomarker measuring, and medical diagnostics. This specificity, together with their catalytic activity, enables nanozymes to play a crucial role in the advancement of immunoassay techniques for various applications, ultimately leading to improved disease diagnosis, therapeutic monitoring, and research capabilities.

According to different signaling modes, such as colorimetric, fluorescent, chemiluminescent, electrochemical, electrochemiluminescent, surface-enhanced Raman, photoelectrochemical signals, and other types of signals, as well as the combination of multimodal signals, the immunoassays based on nanozymes are specifically categorized [68].

Nanozymes have been utilized frequently as effective substitutes for natural enzymes in immunoassays due to their simple manufacture, low cost, and great stability. In general, a colorimetric immunoassay based on nanozymes is created by using the antibody that binds to the nanozymes to catalyze the color reaction either directly or indirectly. The change in color or signal strength caused by the catalytic reaction is proportional to the target concentration [68]. To measure various proteins, bacteria, and other targets with several antigen sites on their surfaces, a sandwich structure is typically produced in the nanozyme-linked immunosorbent assay (NLISA) [68]. Amorphous Ruthenium Telluride RuTe2 (a-RuTe2) nanorods were used by Yan et al. to create a typical colorimetric enzyme-linked immunosorbent test (ELISA), which may be used to identify prostate-specific antigen (PSA) molecules [69].

A photosensitive colorimetric immunoassay for the detection of carcinoembryonic antigen (CEA) has also been made employing light-responsive nanozymes besides to the mimic peroxidase activity [70]. As a nano-biological probe, protein G functionalized nanomagnet-silica nanoparticles decorated with Au@Pd (Fe_3O_4@SiO_2-NH_2-Au@Pd0.30NPs-protG) were used to create a colorimetric immunosensor for the detection of tumor-associated anti-p53 autoantibodies (antip53aAbs). In addition, to having a high affinity for the anti-P53aAbs that were collected, Fe_3O_4@SiO_2-NH_2- Au@Pd0.30NPs-protG also shown excellent catalytic performance for the oxidation of 3, 3, 5, 5-tetramethylbenzidine (TMB) [71]. The highly controlled $Cu(OH)_2$ nanocages could be used as labels to capture the proliferating DNA primer and the secondary antibody of the immunoreactions. These two molecules were then amplified by a hybridization chain reaction, resulting in a significant amount of DNAzymes (G-quadruplex/Hemin) on the surface of the $Cu(OH)_2$ nanocages[72]. The PB NPs' high peroxidase-like activity and the excellent catalysis brought on by the colorimetric reaction significantly increased the detection sensitivity of prostate-specific antigen (PSA) [72].

Biomarker enrichment is frequently accomplished using magnetic separation. For the highly sensitive detection of influenza virus A, a magnetic nanozyme-linked immunosorbent assay (MagLISA) developed [73]. Three functional components were combined into the MagLISA: (i) magnetic nanobeads for biomarker enrichment, (ii) gold nanozymes for an artificial peroxidase catalyst, and (iii) anti-hemagglutinin monoclonal antibody for a particular recognizer [72]. The conventional competitive colorimetric technique frequently displays a signal-off state that is unable to produce noticeable color changes. In order to solve this issue, Ma et al. switched from the conventional signal-off model to a signal-on model using polyvinylpyrrolidone (PVP)-capped Pt nanocubes (PVP-PtNC), a peroxidase-mimicking nanozyme. This was helpful in increasing the sensitivity of drug detection [74]. Mn_2O_3 showed the highest oxidase activity when MnO_2, Mn_3O_4, and other compounds were compared [75]. A covalent coupling approach was developed due to Mn_2O_3's poor physical ability to bind to antibodies.

A one-step indirect competitive ELISA (icELISA) was created to detect isocarbophos by coating Mn_2O_3 with amine-containing silane and linking the antibody with glutaraldehyde. The IC50 value achieved was 261.7 ng/mL [72]. In immunochromatographic assay (ICA), nanozymes are frequently utilized as markers. The competition method and the double antibody sandwich approach are the two primary divisions of the ICA detection principle. The competition approach is appropriate for the identification of small-molecule antigens that are unable to bind to both antibodies, whereas the double antibody sandwich method is appropriate for the detection of polyvalent antigens having at least two antigenic determinants [72]. Nanozymes are frequently employed in ICA as markers.

In ICA, some nanomaterials with innate enzymatic activity can both stimulate the substrate's color development and display color on their own fluorescence[76]. In order to quantify antigens or antibodies by a particular reaction between antibody and antigen, an immunosensor uses an immune reagent as a molecular detection unit and a fluorescent reagent or enzyme as a marker.

The performance of fluorescent immunoassays is high sensitivity compared to colorimetric immunoassays. A single fluorescence signal, however, is easily obstructed by environmental factors. An approach that eliminates interference from the instruments and environs is the ratiometric fluorescence technique, which provides built-in self-calibration by combining two emissions (a reference and a detection signal) [77]. The enzyme must typically be tagged on the antigen or antibody for the standard chemiluminescence immunoassay (CLIA) analysis. The CLIA can be coupled with lateral flow assays to produce very sensitive and portable chemiluminescence detection. To create a high-sensitive point-of-care testing (POCT) method for SARS-CoV-2 antigen detection, Liu and colleagues, for example, created a novel nanozyme-based chemiluminescence paper assay [78]. This led to the development of the chemiluminescence imaging nanozyme immunoassay (CINIA), in which the nanozymes (carboxylated copper monosulfide nanoparticles, CuSNPs) were used as catalytic tags for measuring multiplexed cytokine [79].

Electrochemical immunoassays have gained a lot of attention in the field of immunosensing because of its advantages of low cost, high sensitivity, outstanding selectivity, and exceptional portability [80]. For signal amplification so far, the majority of nanozyme-based electrochemical immunoassays have used nanozymes that resemble peroxidase [72]. High luminescence analysis sensitivity and high specificity for the antigen-antibody reaction are both characteristics of the electrochemiluminescence (ECL) immunoassay [72]. The luminol-H_2O_2 system may be electrochemically reacted with using the lead sulfide nanocrystals (PbS NCs) nanozymes, which might also improve the luminol's ECL response [81].

Surface-enhanced Raman spectroscopy (SERS) is a type of optical sensing technology used to detect the rough surface of nanomaterials. It has the benefit of high sensitivity, in situ non-invasion, and a distinctive molecular fingerprint spectrum that is frequently employed in immunoassays [72]. Electrochemiluminescence (ECL) immunoassay and photoelectrochemical (PEC) immunoassay are fundamentally same, although the detection method is opposite. The optical signal serves as the excitation source for the PEC immunoassay, which then detects the electrochemical signal. Because the input and output signals have different energy forms, the PEC immunoassay has a low background signal and can attain relatively high sensitivity [82]. A straightforward, affordable PEC immunoassay for the ultrasensitive detection of target biomarkers was created using a high-activity Fe_3O_4 nanozyme as the signal amplifier and $ZnIn_2S_4$/ZnO-NRs/ITO photoelectrodes as the PEC matrix [83].

In addition to providing a colorimetric, fluorescence, photothermal, and electrochemical response, nanozymes can engage in catalyzing various reactions. Dual mode or even tri-mode (colorimetric/photothermal/chemiluminescent) immunoassays have lately become popular. Examples include colorimetric/fluorescent, colorimetric/electrochemical, colorimetric/photothermal, and colorimetric/SERS [84]. A multimodal sensing technique can offer more accurate and thorough information than a single detection modality. It is believed that the multimodal immunosensing pattern, which is a trend that generates immunoassays with adequate dependability and precision, may minimize the background signal and erroneous findings by merging the advantages of several signaling techniques together [80].

It is possible to use a nanozyme label to provide different signals for multimodal detection since nanozymes can catalyze several reactions to produce colorimetric, fluorescent, and electrochemical response at the same time [85, 86]. The created nanozyme-based immunosensors not only contain the inherent benefits of standard ELISAs but are also more stable and affordable by researching artificial enzyme mimics to substitute the natural enzymes used. As a result, the employment of such a nanozyme and immunosensing combination in clinical diagnosis, food safety, environmental monitoring, and other fields has shown potential. Designing and creating desirable nanozyme-based immunoassays and microsensors is anticipated to get more interest from the sensor research community [80].

Therapuetic Applications of Nanozymes

Nanozymes have become a viable paradigm for therapeutic applications in recent years, utilizing their catalytic capability to address a variety of medical problems. The advantages of these nanomaterials, which imitate natural enzymes, include increased stability, controllable catalytic activity, and simplicity of functionalization. Nanozymes have demonstrated enormous potential for transforming therapeutic approaches in a variety of fields by utilizing their special features.

Antibacterial, Antioxidant and Antifouling Applications

Nanozymes are a family of nanomaterials that resemble enzymes and have a variety of uses in the study of antibacterial, antioxidant, and antifouling agents. These artificial nanostructures are designed to imitate the catalytic functions of real enzymes, offering a flexible platform for medicinal, environmental, and industrial applications. The continued threat of antibiotic resistance to global health has prompted research into alternate strategies. Drug-resistant bacteria emerge as a result of bacterial biofilms, which show a variety of phenotypic alterations and are resistant to many antibiotics now in use [87]. Clinical anti-infection therapy is made more challenging by drug-resistant germs, primarily because of side effects, unpredictability, lengthy treatment times, and expensive costs [88].

Nanozymes have demonstrated great antibacterial potential, aiding in the creation of alternate methods for dealing with bacteria that are resistant to antibiotics. They can kill bacteria by producing reactive oxygen species (ROS), rupturing bacterial membranes, and altering intracellular pathways, among other processes. Through the production of ROS during catalytic activity, nanozymes provide a strong antibacterial therapy option. For instance, by causing ROS-mediated bacterial cell damage, copper-based nanozymes exhibit extraordinary antibacterial action [89]. The effective breakdown of H_2O_2 in the presence of Fe@MoS_2 has been applied to the detoxification of mustard gas simulant and the antibacterial activity. With the application of a low concentration of H_2O_2, the combined action of Fe@MoS_2 and H_2O_2 demonstrated outstanding antibacterial activity against the drug-resistant bacterial strains methicillin-resistant *Staphylococcus aureus* and *Escherichia coli* [90].

In addition to this, an alternate method of food preservation is provided by nanozymes, which have good broad-spectrum antimicrobial activities [91]. [92] created new and appealing nitrogen-doped carbon nanodots (N-CNDs) as effective metal-free artificial nanozymes that inherit the bacteriostatic property of tea polyphenols and light-triggered oxidase-like catalytic activity to synergistically and efficiently limit bacterial viability. A Cu nanozyme (Cu-N-C) with inherent peroxidase and oxidase-like activity was developed. During oxidase-catalysed reactions, Cu-N-C can produce OH and O_2—both of which have potent antibacterial properties [93].

Through the use of a novel technique called selective laser welding in liquid, a SOD-like nanozyme with excellent antibacterial activity based on a hybrid Ag/CeO_2 nanocomposite was quickly and easily created. Under visible light illumination, this produced nanozyme had a strong antibacterial action against *S. aureus*, with a sterilization rate as high as 82.4%. These sterilization rates were 2.93 and 2.99 times greater than those of pure Ag and Cerium Oxide CeO_2, respectively. In order to reduce the CeO_2band gap and increase visible light harvesting, Ag nanospheres were anchored to the surface of CeO_2 nanosheets. This caused a spike in visible light harvesting and increased antibacterial activity [94]. Such focused strategies have the potential to reduce bacterial infections while avoiding conventional antibiotic resistance mechanisms.

Attention has been drawn to nanozymes as potential antioxidants, providing defence against cellular damage and illnesses linked to oxidative stress. Their antioxidant capabilities are aided by their capacity to scavenge reactive oxygen species such as superoxide radicals and hydrogen peroxide. Effective antioxidant therapy is required because oxidative stress plays a significant role in many diseases. With their inherent peroxidase-like activity, nanozymes offer a cutting-edge method for controlling cellular redox equilibrium. For example, cerium oxide nanoparticles (CeO_2 NPs) have prospective applications in age- and neurodegenerative-related diseases since they scavenge ROS and reduce oxidative stress [95]. In order to reduce oxidative damage and inflammation, these nanomaterials can mimic the action of native enzymes like catalase [96].

Nanozymes been proven to have antifouling capabilities, and they can be used to stop biofilms, algae, and other fouling agents from adhering to surfaces. Their catalytic activity can prevent fouling organisms from sticking to surfaces and encourage self-cleaning ones. Antifouling techniques have been developed in response to biofouling, a chronic problem in a variety of medical settings. The development of antibiotic-resistant bacteria and genes has made them major environmental contaminants, increasing the risk to human health and ecological security [97]. Due to their catalytic activity, nanozymes provide a dynamic strategy by preventing the production of biofilms. Using biocide-containing surface coatings, including heavy metal compounds and tributyltin, is a common strategy for preventing marine biofilm, although this method has major ecological consequences for non-target species due to its nonselective fatal toxicity [98].

However, a number of challenges, including low stability, poor environmental adaptation, and strong sensitivity towards a single component, hamper the use of natural enzyme-based antifouling agents. Nanozymes have become new instruments for creating innovative antifouling agents due to their high stability, favourable environmental safety, and scalable manufacturing capabilities [99]. For example, nanozymes having HPO-like activity effectively inhibited the development of biofilm and fragmented the mature biofilm, thus minimizing the fouling of the surface of underwater structures in the marine environment [99]. Many mimics, including POD, OXD, and hydrolase, have been found to have tremendous antifouling potential [100].

An intriguing method for improving the redox capacity of nanozymes is heteroatom engineering, which may provide a novel route for creating high-performance nanozymes that imitate HPO through the use of transition metals. For instance, Wang group showed that Co-doped MoS_2 has antifouling capabilities because it had 2 and 23 times more HPO-mimicking activity than Ni-doped MoS_2 and pristine MoS_2, respectively [101]. Natural organic matter (NOM), especially humic substrates from surface water, can easily create a compact fouling layer on the filtration membrane during the treatment of drinking water [102]. These nanoparticles can stop biofilm components from adhering to surfaces and colonizing them by enzymatically degrading them [103].

Treatment for Cardio Vascular Disease

Globally majority of deaths are caused by cardiovascular disease (CVD), which has a dismal outlook. Nanotechnology offers enormous potential in cardiovascular regenerative medicine because of the special physical, chemical, and biological features of nanomaterials and nanostructures, as well as the recent development of biomedical devices, contrast agents, and other things [104]. To overcome the limits of natural enzymes, enzyme mimicry is becoming more and more popular in this regard nanozymes are employed in the imitation of enzymes. The anti-inflammatory, anti-aging, neuroprotective, cytoprotective, dental biofilm-removal, antioxidative, and antithrombotic properties of nanozymes employed in various therapies are affected [105].

Cardiovascular nanomedicine seeks to advance in *vivo* and ex vivo biomarker imaging and detection, increase tissue regeneration, and enhance drug delivery to solve current CVD and therapeutic difficulties. Drug delivery methods include direct injection and nanocarriers [106]. Targeted therapy is beneficial for cardiovascular disorders, which are a major cause of morbidity and mortality worldwide. Studies involving the particular imaging or therapy of atherosclerosis have included metal nanoparticles. A membrane receptor from the macrophage lineage is referred to as CD163. The existence of intraplaque haemorrhagic sites or asymptomatic plaques is indicated by increased levels of CD163 expression in areas associated with inflammation, according to studies on atherosclerosis [104]. Atherosclerotic plaque sites have been shown to exhibit significant permeability and retention effects akin to solid tumors. It is demonstrated that, when the overall atherosclerotic volume is decreased, silicon-gold hybrid nanoparticles and gold nanorods work in conjunction with Photo Thermal Therapy (PTT) [107].

The primary emphasis of current research is endothelialisation following stent implantation. As supersensing components in biosensors based on conjugated nanomaterials, carbon dots and mesoporous silica complement each other effectively. This idea can therefore help in the early diagnosis of Myocardial Infection (MI) by providing the necessary data for subsequent therapy [108]. Through their control of oxidative stress and lipid metabolism, nanozymes have the potential to treat cardiovascular diseases. Building liposomes or PLGA nanoparticles to transport proteins or genes like vascular endothelial growth factor and angiopoietin is the basis of the research [109]. The sensitivity of the carbon dot-based biosensors was improved by the inclusion of silver nanoparticles, graphene oxide, and mesoporous silica.Clinically speaking, in-stent restenosis develops when inflammatory cell aggregates, excessive smooth muscle cell proliferation, and platelet aggregation take place.

Cancer Therapy

Early detection of cancer is essential for effective treatment. Patients with renal cell carcinoma provide as an excellent example of how delayed diagnosis has a significant detrimental influence on survival rates [57]. Up to 99% of patients with early-stage renal cancer survive, compared to only 16% of those with second- or higher-stage renal cancer [110]. When compared to conventional therapy, nanoparticle formulations typically display increased therapeutic efficiency with fewer side effects due to greater bio distribution and enhanced tumor accumulations [111–113]. Due to their specific tumour targeting and ROS-induced cytotoxicity, nanozymes have attracted interest in the field of cancer treatment. Catalase-like nanozymes can increase the production of ROS in cancer cells, which causes apoptosis and slows tumour growth [114]. Co-CDs have the capacity to precisely catalyze H_2O_2 in cancer cells, producing a variety of reactive oxygen species and ultimately killing the cancer cells. This has potential use in tumor catalytic therapy [115].

For instance, it has been shown that proteolytic enzymes (such as matrix metalloproteinases, serine proteases, and cysteine cathepsins) promote the growth of tumors [116]. Nanozymes have been successfully used to detect cancer-related genes, molecules, and cells, and can act as probes for precise imaging due to their inherent characteristics of nanomaterials, which include superior catalytic activity, low cost, high stability, and multifunctionality [57]. Furthermore, by permitting regulated release and site-specific accumulation, nanozyme-based drug delivery systems improve therapeutic effectiveness.

Orthopaedics

Since they aid in tissue regeneration and wound healing, nanozymes have found use in orthopaedics. Functionalized nanozymes are useful in tissue engineering scaffolds and orthopaedic implants because they help speed up bone mineralization and encourage tissue repair [117].

Nanozymesin Foodindustry

Food Industries consists of various activities that involve processing, conversion, preparation as well as preservation and packaging of food. Improvements in food processing are mainly focused on preservation technologies and assurance of food safety analysis, leading to an increase in demand of processed food and drink, especially in the developing countries, therefore various different technologies have been developed such as machinery and robots to reduce human labor and implementing nanotechnology for processing, packaging and preserving of food [118].

Food contaminants contain biological hazards, heavy metals and other objects that can enter the food products during the manufacturing process and thus the food safety analysis plays the important line of defense to ensure the food safety, Though the World Health Organizations (WHO) have taken plenty of steps to protect the humans from health hazards yet the danger exists which cannot be removed even by using conventional techniques such as chromatography, mass spectrometry, high performance liquid chromatography as they are complicated and time consuming methods whereas food contamination can take place during food processing or transporting or while sanitization and clearing wastes from the industries [119]. Natural enzymes have been explored to construct biosensors yet due toits drawbacks the nanozymes have been considered to have enzyme like activities with characteristics of both natural as well as artificial enzymes and can attract the attention in the fields of sensing and biosensing, medicine, and disease treatment [120].

Sensing systems have also been improvised into new heights such as detecting the presence of pathogens in milk and ice-cream with the help of smart phones. Antibiotics such as kanamycin, enrofloxacin have great therapeutic effects on the bacterial infectious diseases however excessive residues and metabolites that remain in the meat, eggs, milk and animal derived food will eventually accumulate along the food chain and causes danger in human health. Liet al., reported Fe-MIL-88NH_2 metal organic framework can enhance the Chemiluminescence of luminal H_2O_2 in the milk sample [121]. Nanozymes and its vital roles in various sectors of food quality analysis are depicted in Fig. 4.

Fig. 4 Depiction of nanozymes in food quality analysis

Detection of Antioxidants in Food Samples with the Help of Nanozymes

In food industry, antioxidants are widely used in food processing and food packaging materials, having the potential to slow down the antioxidation process ofbiologicalmoleculessuchaslipidsandproteinsthatcanleadtorancidity, reduced shelf-life as well as the development of undesirable taste and fragrance, resulting in the deterioration of texture and quality of nutrient substances [122].

New gold doped copper hexacyanoferrate (Au@CuHCF) nanozyme thathas good stability is prepared based on excellent antioxidant activity. Au@Cu-HCF nanozyme replaces the natural enzyme to determine antioxidant activities in the food samples that aids to determine the electro donating antioxidant species which contributes towards the total antioxidant capacity (TAC). This smart phone-based software is developed and successfully applied to check with the TAC of lotus root extract and fruit beverage samples [123].

The natural antioxidant enzymes consist of various limitations such as high cost, lowstability, difficult storage and poor reusability. Nanozymes becomes an advantage in the field of nanotechnological developments that are reported to improve the limitations of these natural antioxidant enzymes. One of such antioxidant enzymes are catalases (CAT) are natural enzymes containing iron porphyrinat-theiractivesitesandcancatalyzethedegradationofhydrogen-peroxideto form molecular oxygen and water [124].The quantification of antioxidants is considered to be an important aspect for determining the TAC in food which are done by performing important assays based on gold and silver nanostructures (e.g., nanorods, composites, CeO_2, TiO_2 or carbon-based nanomaterials such as graphene and carbon nanotubes interfaced as electrochemical structures [125].

Chain-breaking antioxidants (e.g., glutathione and vitamin E) act by competing with the substrate for the intermediate radicals, generated during chain propagation. Thus, chain-breaking antioxidants terminate free-radical chain reactions through the elimination (scavenging) of radical intermediates through electron donation. CAT enzyme in the food industry referred to as the glucose oxidase has established industrial applications of enzymatic and molecular antioxidants combination that is used during milk processing and for the elimination of O_2 from wine prior to bottling. In the baking industry, the CAT enzyme is also added to remove H_2O_2 from milk, as well as glucose from egg white. In addition, the CAT enzyme is also incorporated in food wrapper stop revent oxidation and control the quality of food [126].

Highly stable carbon supported Co-Ir nanozyme determines the TAC and excellent durability of pH range, temperature and high salt concentration in food samples like detecting the concentration level of ascorbic acid (vitamin C) as well as its tablets and also the fruits. Heavy metals and certain objects can be detected in food items with the help of magnetic nanozymes that are made up of carbon materials which consists of improved detection sensitivity [127]. Therefore, using nanozymes we can test the presence and activities of antioxidants for food safety analysis can be done.

Food Proteins and Nanoparticles

As nanozymes are defined to be the nanoparticles that express the properties of an enzyme, nanoparticles are closely associated with the detection of food proteins for detection [128].

Table 3 Food proteins and conjugated nanoparticles

Food Proteins	Conjugated Nanoparticles
Beta-lactoglobulin	AuNP (gold nanoparticles)
Bovine serum albumin	Gold-198, CuS (Copper Sulphide)
Alpha-lactalbumin	Zinc Oxide Nanoparticles
Casein	Silver conjugated nanoparticles
Lactoferrin	Iron oxide nanoparticles
Gelatin	CuO nanoparticles

Few Important food Proteins and Their Nanozyme Properties

Beta-Lactoglobulin

Beta-lactoglobulin globular protein is found to be present in the milk of many mammalian species such as cows, pigs, sheep, and horses (Table 3). There are a wide range of functions involving the interactions that happen between the protein residues and food ingredients [129], thus individuals and mainly infants who are milk allergic are sensitive towards this particular protein. Gold nanoparticles such as the AuNPs adsorbs the beta-LG, reduces the hypersensitivity due to the formation of gold-Sulphur covalent bonds leading to the biological denaturation and disruption of the disulphide bonds present in the globular protein reducing the content of beta-sheet therefore decreasing the stimulation of anaphylaxis in humans due to the consumption of milk products [130].

Bovine Serum Albumin

Bovine serum albumin (BSA) protein is derived from cow and is found mostly in many meat dishes such as beef, eggs as well as chicken that can cause anaphylaxis therefore nanozyme based biosensor using Au cluster that can help in detecting BSA for food safety [131]. BSA in conjugation with gold nanoparticles used to detect the covalency in proteins and results in creating specific changes useful in the food processing field [132].

Casein

Casein protein is found in milk, cheese, yogurt and other dairy products. This particular protein can be combined with AgNPs which consists of antibacterial properties to protect food from infectious pathogens such as *Acinetobacter baumannii* by forming a combination of clusters and works as a layer of antibacterial coating upon devices for detections [133, 134].

Gelatin

Gelatin is used in various forms in the food industry because of its properties to prevent crystallization of sugar and ice and to act as an emulsifier and an extender. Gelatin is found to be added in frozen pies, ice-cream, cottage cheese and also used as a food packaging material as a CuO and ZnO based gelatin films [135, 136].

Alpha-lactalbumin

Alpha-lactalbumin (α-La) is an important protein that is found in milk products and the interaction between this protein and ZnO nanoparticles creates a protein conjugate. Alpha lactalbumin when in its intermediate state can be used as anti-turmeric agents and can suppress certain type of food reactants present in the food that can cause allergies and unhealthy reactions to the body [126].

Lactoferrin

Lactoferrin is a glycoprotein present in butter, cream cheese, yogurt and processed meat, consists of antiviral properties and is called as an iron containing protein and therefore iron oxide nanoparticles can be conjugated with lactoferrin for protein separation as a food analysis technique [137].

Nanozyme Based Detection of Sugars

Many different types of sugars can be seen in a wide variety of food such as fructose, galactose, lactose, maltose, sucrose that are naturally present in vegetables, fruits, molasses, dairy productsand other beverages (Table 4). Among the sugars, glucose is reported to be the most commonly occurring type of sugars in the food industry and is abundant in human life thus leading to risk factors in health such as diabetes. Detection of such a health risking condition can be determined by using various testing methods. One such would be the colorimetry sensors of gold particles. It is feasible to create a nanozyme that can serve as an oxidase by altering the surface of iron oxide nanozymes or glucose oxidases, or by combining the two. Since it supplies a peroxidase-like nanozyme with hydrogen peroxide to cause a color change or emit light in colorimetric or fluorescent biosensors, oxidase activity is important in this assembly [138]. Example of detection of glucose in food (Fig. 5) can be done by using the ferrous ions based nanozyme called Gox@GA-Fe (Glucose oxidase integrated with gallic acid) [139].This Glucose oxidase enzyme is a glycoprotein that possesses orthophosphate proteins and consists of unique varieties of properties such as showing resistance to precipitation and stability, dispersibility in water, substrate specificity, therefore allowing the constructed biosensors in giving improved results as a response to glucose monitoring [140]. While direct monitoring the blood glucose level was not always easy for few patients due to fingertip inflammations and infections, colorimetric biosensors were designed with the help of ferrometric nanozymes, example - Fe_3O_4 NPs, Co_3O_4, graphene oxide and also peroxidase activity of iron oxide nanocomposites. In the case of glucose oxidase metal integrated enzyme, it achieves high sensitivity and high analytical performance in biomolecular level detection [141].

Table 4 Methods of testing food samples to detect sugars along with the nanomaterials

Technique	Analyte Sugar Samples	nanomaterial	Food sample used	Reference (s)
Electrochemical sensor technique	Sucrose, lactose, fructose, glucose	Graphene-Cu, CNTs-Cu NPs	Banana and bovine milk	[139]
Colorimetric method	mannose, maltose, fructose, galactose, lactose	AgNPs (silver nanoparticles)	Sugar-Sweetened soft drinks, food and beverage matrices	142
Electrocatalytic/ Electrochemical method	Glucose, fructose	AuNPs, C-AuNPs (Graphite-Au nanoparticles composite)	Honey, red grapes, fruits and also fruit juices	[143]
Photoelectrochemical sensor	Glucose	Au/TiO_2NTs	-	[144]

Detection of Ions in Food Samples Using Nanozymes

Metal ions can be found in particular beverages such as apple juice, red wine and stout, therefore requires detection of these metal ions in nutrition are considered to be a necessity to check its toxicity which can be performed with the help of nanozymes and nanoparticles [145].Nanozymes can be functionalized with vitamins to detect the ion contents.

Fe^{3+} Ions

In order to determine the Fe^{3+} ions in food samples, Vitamin B_{12} was used to functionalize the biological silver nanoparticles (FeAgNPs). The results of testing baby food products, cereals showed around the range of 74–95% ion content[146].

Na^+ Ions

Consumption of food containing high amount of sodium ions can lead to high blood pressure therefore food testing is necessary to analyze and limit the amount of Na+. Electrochemical sensors are developed with the help of several nanomaterials such as carbon based, metal based nanocomposites. Silver nanoparticles having high compatibility, low toxicity and graphene oxide (GO) having electronic properties which makes it efficient to be used as the nanozyme material in electrochemical sensor to determine the Na+in fish sauce, seasoning powder of instant noodles and other items [147].

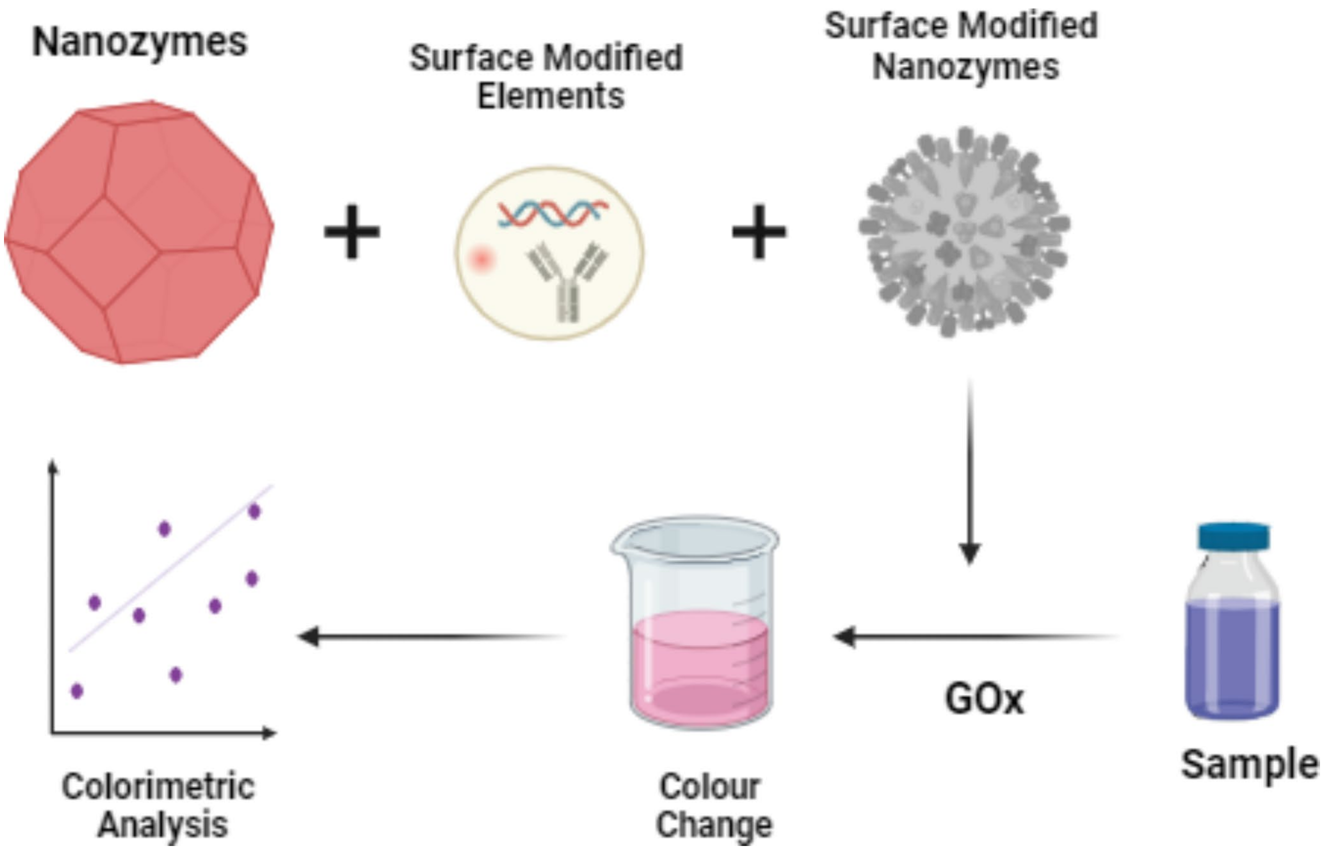


Fig. 5 Illustration of nanozyme based biosensor for detection of glucose using colorimetric shift of the sample

Cu^{2+} Ions

Copper ions are reported to be constantly detected to be present in the water bodies. Water is essential and is used by humans, animals and plants therefore when consumed in various manners, almost all food samples are either washed or cooked using water and therefore when used with the presence of these detected copper ions, it can lead to severe conditions such as kidney damage and other infections.

Detection of Pesticide Residues Using Nanozymes

Pesticides can mainly be found in fruits and vegetables as they are grown and harvested in the agricultural field where agrochemicals are commonly used. If the food products are harvested earlier than its time then more amount of these residues can be seen remaining which becomes hazardous to health for e.g., on the outer peel surfaces [148]. Nanozyme sensors that consist of nanozymes that mimic natural enzyme catalytic activities involves nanomaterials that belong to the group of oxidoreductases such as oxidase, peroxidase that help in absorbing the substrates and giving out successful results [149]. In addition there is a colorimetric sensing platform which is used for detecting pesticides with paraxon which used GeO_2 nanozymes consisting of peroxidase activities and resulting in oxidase type of capabilities when related with the detection systems [150].

Detection of Pathogens in Food with Nanozymes

Many pathogens cause foodborne illnesses such as *E. coli*, *Salmonella typhimurium and Listeria monocytogenes.* Nanozyme biosensors are designed as a single detection mode feature as a colorimetric technique by allowing the growth of platinum nanoparticles (Pt) on the surface of polymer nanospheres which are carbonyl functionalized for the detection and identification of *S. typhimurium*, which can be mostly detected in milk samples [150, 151].

S. aureus is a foodborne pathogen that causes food poisoning due to contamination of processed food samples such as meat and dairy products. *S. aureus* produces wide range of toxins which when consumed continuously through different food items will lead to illness and food poisoning [152].Co_3O_4 is defined to be a magnetic nanozyme which encapsulates *S.aureus* [150]. Pt-Ps is another nanozyme that exhibits peroxidase activity and can detect the presence of *S. aureus* [153].

Vanillin, a vanilla flavor enhancer, is used in food and beverages due to its therapeutic, antidiabetic, antibacterial, and anticancer properties. However, it can cause liver and kidney infections in infants due to high milk consumption.Fe_3O_4@Polyalanine nanoparticles are used for sensing and synthesizing magnetic effects, and when applied as a coat on sensors creates a separation of vanillin in milk powders [154].

Challenges of Using Nanozymes in Food Safety Analysis

The catalytic activities of nanozymes when compared with the natural enzymes on reacting with sensing platforms to detect food pathogens are low and is addressed as an issue that is to be considered and make a solution for the nanozymes to exhibit healthy and high catalytic properties. Selection of materials and nanoparticles-based enzymes according to the analysis of ions and components of food detected is reported to be tough as not all nanomaterials always match with the required detection targets [155].

Nanozymes and its Role in the Environment

The environment, a complex interaction between humans and the physical world, is influenced by biotic and abiotic factors. Industries, while providing resources, are also contributing to pollution and health threats due to human behavior [156]. Nanozymes are recognized to play the role to mimicking natural enzymes for the detection of environmental pollutants by environmental monitoring techniques [157].Peroxidase (POD) nanozymes are being initiated for its catalytic activity as it can detect and measure the content of acid rain, hydrogen peroxide present in rainwater as well as the heavy metals from the environmental samples. Colorimetric based nanozymes sensors are designed for the screening of many substances like pesticides, organophosphorus compounds and ensure particular reactions between the nanozymes and the corresponding environmental agents [158].

Nanozyme sensing systems consists of additional features such as magnetism, fluorescence and conductivity that give an additional advantage on sensing properties [143]. Nanozymes are said to consist of inherent toxicity that risks its self-capacity for widespread usage therefore is considered very important to evaluate the functions performed by the nanozymes during biosphere damage and monitor its activities within the environment [157]. The nanoscale materials are specifically developed to sense the content of H_2O_2 in rainwater in the environmental matrices. Pollutant sensing is based on integrating nanozymes with aptamers [158].

Ellington, Szostak and many other scientists have discovered and reported aptamers to be a new class of nucleic acid which portrayed the various characteristics such as stability, flexibility. A nucleic acid that is small in size capable of being designed as an aptamer-based biosensors that are used for detecting proteins, chemicals and other molecules in biological samples [159].

Detection of Pollutants

Environmental pollutants are chemicals that are found at high level. The environment is reported to be constantly polluted with inorganic ions, metallic compounds, radioactive isotopes, that turns out to be toxic to the environmentand creating volcanic activity, metal corrosion, soil erosion, sedimentation and resuspension [160].

Metal Pollutants

Heavy metals are the most common pollutants found in soil, water, smelting, mining, leather tanning, causing health threats when natural pollutants mix up with the food consumed leading to vomiting, kidney disorders, and also in extreme cases can even lead to death. Therefore, detection of these metal ions with the metallic based nanoparticles allows the detection by depicting a change in color forming an aggregation and binds to the metal ions and results in a resonance [161].

Phenolic Pollutants

These pollutants are present to be plenty in the environment found as discharges in the wastewater, and food matrices. Fe_3O_4 nanozymes with peroxidase activity implemented in colorimetric based sensors can detect and quantify the amount of phenolic compounds present by catalyzing the coupling of phenolic species and 4-AAP (4-aminoantipyrine) in the presence of H_2O_2 resulting in a color change indicating the target compound. Chlorophenol, nitrophenol and aminophenol are common pollutants that were analyzed and reported [162].

Organic Pollutants

Herbicides, pesticides, dyes, antibiotics are some of the common organic pollutants that are released by the paper, leather mills (Table 5) and as well as the food industriesare considered to be carcinogenic in nature and termed to become poisonous to human health [163].Copper peroxide based citric acid nanozyme is rigorously used for the detection of organic pollutants in the environment such as the sulfonylurea herbicides in water and to suppress the bacterial activities present in soil[164]. Organophosphate pesticides

Table 5 List of Nanozymes used to detect pollutants and their techniques

Technique	Nanozyme used	Enzyme like activity	Detection of pollutants	Source of Pollutants	References
Surfaced enhanced raman spectroscopy	MOF based nanozymes (AgNPs and AuNPs)	Peroxidase (POD)	Cationic dyes e.g., crystal violet	Wastewater e.g., pond water	[166]
Electrolytic method	Cysteine-histidine Cu	Laccase	Phenolic pollutants	Environmental and biological samples	[167]
Colorimetric method	$NiCo_2O_4$ @MnO_2	Oxidase, peroxidase	Hydroquinone (Organic pollutant)	Naturally occurring in plants and animals	[168]
Colorimetric method	Magnetite based Fe_3O_4	Peroxidase (POD)	Oils, methyl orange, organic dyes, arsenic	Water and soil sediments	[169]
Surfaced enhanced Raman spectroscopy	Au@AgPt NPs	Peroxidase (POD)	Mercury (Hg+)	Rocks, soils	[170]
Colorimetric method	MnO2 nanozymes	Catalase	Cu^{2+}, Zn^{2+}, Fe^{2+}	Water samples	[171]
Colorimetric method	AmP nanozymes	Laccase	2,4 Dichlorophenol (2,4 DP)	Bleaching in paper Industry	[172]
Colorimetric method	Au-Pt dumbbell nanozyme	Peroxidase (POD)	*Escherichia coli* as pollutant	Water bodies as a pathogen	[173]

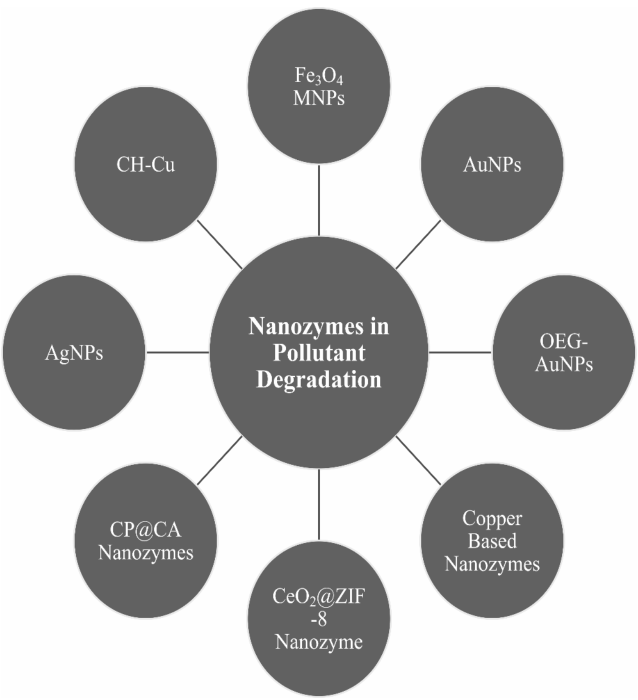


Fig. 6 Various types of metal and organic nanozyme used in pollutant degradation

can be detected with the help of MnO_2nanozymes that exhibits the properties of oxidase as well as peroxidase like activity [165].

Degradation of Pollutants

Degradation of pollutants in the environment is the removal or deterioration of resources from industries and urban fields that create an impact on atmosphere, soil and water due to sewage, heavy metals and other pollutants [174]. Degradation also referred to as remediation of pollutants that can be done employing nanoparticles as they have the ability to react and catalyze reactions, reduces the energy consumption amounts and absorbs the pollutants rather than releasing them into the environment (Fig. 6) [175].

Features of Nanozymes for the Degradation of Pollutants

1. Handling of compounds for biodegradation.
2. Independent operations based on pollutants and its concentration.
3. Management and control over pH, temperature.
4. Highly stable.
5. Easy and Recyclable [150].

Few Nanozymes Used for the Degradation

a) **Fe_3O_4MNPs**.

Considering all types of nanomaterials and nanozyme activities, metal based nanozymes such as Fe_3O_4 MNPs are reported to be the most common type of nanozyme used for degradation of environmental pollutants due to its high peroxidase activity. They were used to degrade pollutants such as phenol, Rhodamine B (Rh B), and organic dyes [176]. In addition to this they are also, used for the degradation of dyes, wastewater that are affecting the environmental health [157].

b) **AuNPs**.

Graphene based gold nanoparticles (AuNPs) nanozymes are designed by hydrothermal reaction that can help in eliminating dye pollutants by adsorption and degradation as they can readily absorb and attract the organic dyes, catalyze the H_2O_2 and generate OH radicals that eliminates the organic dyes which are released into the environment[177].

c) **OEG-AuNPs**.

Hg metal iron is a metal element reported to be highly toxic and causes threat to the environment, aquatic and human health, therefore enabling oligo-ethylene glycol-functionalized gold nanoparticles termed as OEG-AuNPs to enhance the peroxidase activity to form Au-Hg amalgamation in the presence of Hg^{2+} to detect Hg^{2+} in water samples[143].

d) **Copper Based Nanozymes**.

These nanozymes are used to degrade methylene blueas a pollutant in wastewater. Copper nanoparticles consists of high catalytic properties and laccase enzyme like activities that allows it to be the perfect tool for detection of dye pollutants that includes methyl red dye, Congo red, Cresol dye and also other nitroaromatic compounds [178].

e) **CeO_2@ZIF-8 nanozyme**.

Industries release huge amounts of organic pollutants that can cause the dyes to directly be released into the wastewaters and pollute the water bodies. CeO_2@ZIF-8 (Fig. 7) is a type of nanozyme that is known for its surface area, stability, enhancing catalytic activities for the detection and degradation of organic dyes such as Methyl Orange (MO) dye content during wastewater remediation process [179].

f) **CP@CA nanozyme**.

Citric acid modified Copper peroxide is a nanozyme that is widely used for the detection of herbicide residues. Herbicides are used to control the weed growth in crops in the agricultural fields, although continuous usage can lead to threats for the soil and crops. Therefore CP@CA nanozymes are used to reduce the H_2O_2content and Cu^{2+} to Cu^{+} to degrade the presence of nicosulfuron in water and soil [180]. Nicosulfuron is a toxic herbicide which is a huge demand for preserving the weed qualities in crops thus hazardous to the environment as a pollutant [181].

g) **AgNPs**.

Silver based nanoparticles having enzyme like activity has the ability to degrade organic dyes and pesticides that are present in water during wastewater treatments. These nanozymes are also used for plant pesticides and fertilizers [182].

h) **CH-Cu**.

Toxic pollutants such as chlorophenols are considered to be neurotoxic and found to be present in the soil and water. CH-Cu is new found class of nanozymes well known for its catalytic activity, recyclability exhibits laccase enzyme like activities and are reported for the degradation of phenolic compounds[183].

Water Treatment

Surface water becomes a major source of victim becoming a discharge site for most of the toxic pollutants which will consist of heavy metals and pharmaceutical chemical wastes e.g., dams, rivers and streams [184]. These heavy

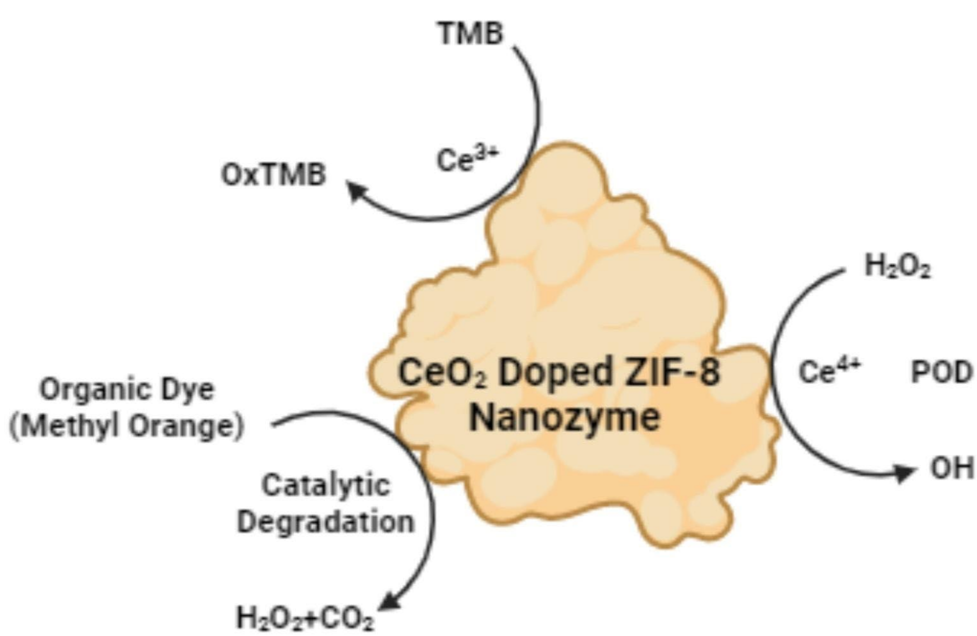


Fig. 7 Catalytic degradation of 3,3’,5,5’-Tetramethylbenzidine (TMB), methyl orange and peroxidase activity of CeO_2 doped ZIF-8 nanozyme in environmental pollutant degradation

metals become sediments in the water bodies and interfere with the aquatic habitats as pollutants, entering into the gills and muscles of aquatic fishes damaging kidneys and intestines and thus when fishes are filtered up for consumption by humans, heavy metals can be analyzed while performing the food processing techniques to process the fishes as food providing as a part of human diet [185].

Reduction of chemicals for water treatment can be implemented when more amount of chemicals which can be found in the natural sources of water can be reduced with the help of nanoparticles and is required to make sure that the synthesis process is rapid otherwise this would cause particle aggregation when the process is for reduction of metal salts. This chemical reduction can be performed with the help of nanozymes that show peroxidase enzyme like activity e.g., AuNPs in combination with *Pseudomonas aeruginosa* designed into a bioelectrode structure that can be used for detecting bacteria and pathogens [186].

Large amounts of carbon-based nanomaterials are being used for removal of dyes from the waste waterof textile industries e.g., GO based nanozymes, Fe_3O_4, TiO_2, graphene, hematite nanoparticles (α-Fe_2O_3) loaded with mesoporous silica to detect the presence of red brick wastes released from brick factories or construction materials from different areas[187].

Other Techniques Employed in Improved Water Treatment

1. To use nanozymes that exhibits phosphatase and peroxidase enzyme like activity to scavenge organophosphorus pesticides and other chemical agents that are found in water samples, as nanozymes contain the capability of retaining and adsorbing magnetic properties that can be considered as an effective way for implementing strategies based on decomposition of pollutants [188].
2. Use of Carbon-based adsorbents that has the ability to allow biological contaminants to bind upon the heavy metals, as carbon has high absorbent capacity also known for its high porosity. Co@CoO/NC nano-cobalt wrapped nanotubes are used to remove rhodamine B, as carbon nanocomposites have the ability to eliminate pharmaceutical contaminants that can be used for the purification of water samples [189].
3. In order to perform wastewater treatment cobalt oxide nanoparticle consisting of catalase and peroxidase enzyme like activities are used which also helps in using its catalytic properties to treat water contaminants [166].
4. Implementation of green nanotechnology techniques that will improve environment and water sustainability [167].
5. **Water Purification**: Usage of Fe-N-C based nanozyme that enhances the oxidation activity in water treatment and is used to degrade hydrogen sulphide (HS) in surface water as well as drinking water. This nanozyme focuses on purifying the water by removal of oxidation of organic pollutants and its toxicity in water samples.

Conclusion

In conclusion, nanozymes have demonstrated their enormous potential to alter multiple industries by emerging as exceptional and adaptable instruments with varied applications across diverse domains. Nanozymes have shown their utility in addressing complex problems and improving existing methodologies, as evidenced by their expanding presence in numerous fields, including food safety, biosensors, immunoassays, therapeutics, antibacterial coatings, antifouling surfaces, environmental remediation, and microbial imaging. The outstanding catalytic capabilities, customizable functions, and biocompatibility of nanozymes will undoubtedly continue to spur creative thinking in a variety of fields as research in the subject advances. The listed sources and the findings discussed in this article serve as examples of the breadth of impact that nanozymes have already proven, highlighting their critical significance in determining the course of science and technology.

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