chemistry

MDPI

Review

Nanozyme-Based Portable Water Purification Systems for Villages and Emergency Situations: A New Approach

Nandini Chauhan [1], Garima Awasthi [2], Mahipal Singh Sankhla [2,*], Kumud Kant Awasthi [2], Rajeev Kumar [3], Narendra Kumar [3], Baljeet Yadav [2] and Haitham Al Qahtani [4,*]

[1] Department of Forensic Science, UIAHS, Chandigarh University, Mohali 140413, Punjab, India; chauhannandini4@gmail.com
[2] School of Basic and Applied Sciences, K.R. Mangalam University, Gurugram 122103, Haryana, India; gariimaa21@gmail.com (G.A.); kkantawasthi@gmail.com (K.K.A.); dryadav4n6@gmail.com (B.Y.)
[3] School of Sciences, IILM University, Greater Noida 201306, Uttar Pradesh, India; rajeev4n6@gmail.com (R.K.); narendrakumar@iilm.edu (N.K.)
[4] Department of Environmental Engineering, University of Technology Bahrain, Salmabad P.O. Box 18041, Bahrain
* Correspondence: mahi4n6@gmail.com (M.S.S.); haitham.alqahtani@utb.edu.bh (H.A.Q.)

Abstract

Access to clean and safe drinking water for all remains a global challenge, mainly for rural populations and areas affected by natural disasters or humanitarian crises. The traditional water quality treatment technologies can work well in laboratory or controlled settings, but they are usually applied under conditions unavailable in these types of conditions. Traditional water quality treatment methods are limited by established infrastructure, expensive operating costs, energy requirements, and the ability to perform in-field water treatment. To improve the barriers of traditional water quality treatment technologies, recently developed scientific discoveries of nanozymes, a new class of nanomaterials with enzyme-like catalytic activity, have shown the ability to decentralise water purification. Nanozymes provide a mechanism for water treatment that does not require the infrastructure or the cost of traditional water quality treatment methods. Also, nanozymes possess extremely high catalytic activity, chemical stability, are inexpensive, and are suitable for a variety of contaminants. This review gives a systematic overview of the development of suitable nanozyme-based portable water purification systems. It shows their catalytic mechanisms, the class of nanozymes used, and the design characteristics related to their working use, also highlighting the developments that consider the specific needs of rural contexts, provide rapid responses to disaster areas, and offer drinking water with reliable, simple, and sustainable apparatus.

Keywords: nanozymes; portable water purification; decentralised water treatment; catalytic nanomaterials; rural water access; enzyme-mimicking catalysts; water contaminant removal; sustainable water technologies

Check for updates

Academic Editors: Anupam Singha Roy and Sekar Karthikeyan

Received: 18 March 2026
Revised: 11 April 2026
Accepted: 16 April 2026
Published: 17 June 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Access to safe, clean drinking water is a basic human right and a key public health need. More than 2 billion people globally, however, do not have safely managed drinking water supplies, with the most vulnerable populations living in rural areas or experiencing humanitarian crises of natural disasters, armed conflict, or shifting of places. The results of drinking water contaminated with pathogens are widespread, directly causing waterborne

diseases and illness, a lack of sanitation, and higher mortality rates in vulnerable groups like children under five [1].

Existing water treatment technologies, including chlorination, reverse osmosis, filtration, and ultraviolet (UV) disinfection, have been developed for use in urban and resource-based communities but are not suitable for limited-resource or disaster-affected areas. Many of these technologies depend on a broader, complex supply chain, and they also need constant access to power, trained technicians, and outgoing supply chains, which include replacement parts and ongoing chemical supply costs [2]. In addition to these day-to-day problems, existing water treatment processes often cannot remove contaminants of emerging concern, such as pharmaceuticals, pesticides, and heavy metals. These substances pose increasing risks to water safety and are hard to remove from the common treatment method [2].

In recent years, nanozymes, a unique type of nanomaterial with catalytic properties like those of enzymes, have emerged as innovative, flexible approaches to water purification. Nanozymes have many advantages compared to natural enzymes, which include stability, reusability, and tunable activity, which can operate in various environmental conditions and portable settings [3]. Nanozymes have shown effective ability to degrade organic pollutants, remove microbial pathogens, and remove heavy metals, thus providing a multifunctional solution to deal with complex water contamination challenges [4].

In rural and emergency situations, when traditional infrastructure is limited, nanozyme-based water filtration has shown promise as a decentralised water treatment method. High stability, adaptable activity, and compatibility with portable systems are among the benefits of nanozymes, nanomaterials with catalytic activity similar to that of enzymes. However, with rapid development, their practical application remains unclear due to a lack of standards, inadequate technological, economic, and environmental analyses, and limited real-world validation.

The review summarises the development, design, and use of nanozyme-based portable water purification equipment, with a focus on their application in rural areas or during emergencies. nanozymes offers new platforms for on-site water treatment in low- or resource-limited settings and provides long-term access to safe drinking water. The review examines the mechanisms, materials, design considerations, and benefits of nanozyme technologies, and provides a more in-depth evaluation of their future as transformative technologies that can deliver nanozyme-based water technologies at affordable on-site detection. The review also considers some of the challenges, mainly environmental safety, selectivity, and scalability, and shows plans that need to be performed to access nanozyme-based platforms at scale in outdoor systems.

2. Nanozymes: An Overview

Nanozymes are a type of engineered nanomaterial that shows natural enzyme-like catalytic functions, making them a built-in substitute for natural enzymes in many fields, such as biomedical, environmental, and industrial applications. The term "nanozyme" is a combination of "nanomaterial" and "enzyme," and it also applies to nanoparticles that can mimic the catalytic function of natural enzymes like as peroxidases, oxidases, catalases, and hydrolases [5,6]. The concept of nanozymes was introduced in the early 2000s, and it became widely accepted after Gao et al. [7] reported on the unique discovery that Fe_3O_4 nanoparticles show natural peroxidase-like activity. A notable study used Fe_3O_4 nanoparticles to catalyse the oxidation of common peroxidase substrates, such as TMB (3,3′,5,5′-tetramethylbenzidine), in the presence of hydrogen peroxide (H_2O_2), mimicking the catalytic functions of natural horseradish peroxidase (HRP). This study provided steps towards the development of stable, cheap, artificial enzymes for different catalytic applications [7]. There have been many

developed nanozymes based on metal oxides, carbon-based nanostructures, metal-organic frameworks (MOFs), and even biomimetic nanocomposites, all designed to act like specific enzymatic functions [6]. The design flexibility and catalytic versatility of the nanozymes make them suitable to be combined with next-generation environmental technologies, including portable water purification platforms.

2.1. Classification of Nanozymes

Nanozymes are mainly classified according to the specific enzyme-like function they mimic, providing a basis for potential applications in biomedicine, environmental remediation, and industrial catalysis. Classification of nanozymes is mainly based on the natural enzyme activity that the nanomaterial mimics. Thus, we can categorise the nanozymes studied into three main groups: oxidoreductases, hydrolases, and superoxide dismutase, etc [6].

The studied class of nanozymes is oxidoreductase-mimicking nanozymes, which include materials with peroxidase-, oxidase-, and catalase-like activities. For example, iron oxide nanoparticles (Fe_3O_4) show natural peroxidase-like activity and catalyse the oxidation of substrates like TMB in the presence of hydrogen peroxide [7]. Cerium oxide (CeO_2) nanoparticles have been shown to display catalase- and oxidase-like activity, which allows them to easily decompose reactive oxygen species [8]. Hydrolase-mimicking nanozymes, like phosphatases and esterases, have been able to catalyse hydrolysis of the phosphate or ester bond, but have been widely studied to degrade environmental pollutants like organophosphates in agricultural surface water [9].

Superoxide dismutase (SOD)-like nanozymes, like ceria and manganese nanoparticles, function by breaking down the superoxide radical into oxygen and hydrogen peroxide; these help to decrease damage caused by harmful oxygen molecules in organisms/systems [10]. This classification is useful for selecting the most suitable nanozyme systems for specific environmental or catalytic contexts, particularly in water purification, where multiple enzymatic activities are often needed for thorough decontamination.

2.1.1. Oxidoreductase-Mimicking Nanozymes

Nanozymes that mimic oxidoreductases are the largest and most studied area of engineered enzymes. They can replicate the catalytic action of natural oxidoreductases that catalyse redox reactions by moving electrons from a reducing agent to an oxidiser. Most of the reactions which they catalyse involve reactive oxygen species (ROS) and peroxides, and have significant roles in applications that include pollutant degradation, microbial disinfection, biosensors and cancer treatment [11].

There are three main subclasses of oxidoreductase-like nanozymes:

(a) Peroxidase-Mimicking Nanozymes

Peroxidase-like nanozymes catalyse the oxidation of a substrate (like 3,3′,5,5′-tetramethylbenzidine (TMB) or o-phenylenediamine (OPD)) with hydrogen peroxide (H_2O_2) in the reaction. The process of co-precipitation for the synthesis and characterization of a carbon-based magnetic nanostructure, along with its peroxidase-like activity evaluated using the 3,3′,5,5′-tetramethylbenzidine (TMB) assay, is shown in Figure 1. The first materials to have this activity were iron oxide nanoparticles (Fe_3O_4), which acted as mimics of horseradish peroxidase (HRP), as shown in the first study of this type by Gao et al. [7] These particles oxidise H_2O_2 to hydroxyl radicals (•OH), which are used to oxidise organic contaminants and pathogens. They are considered for point-of-use (POU) water purification technologies and for colorimetric biosensors because of their stability and efficiency.

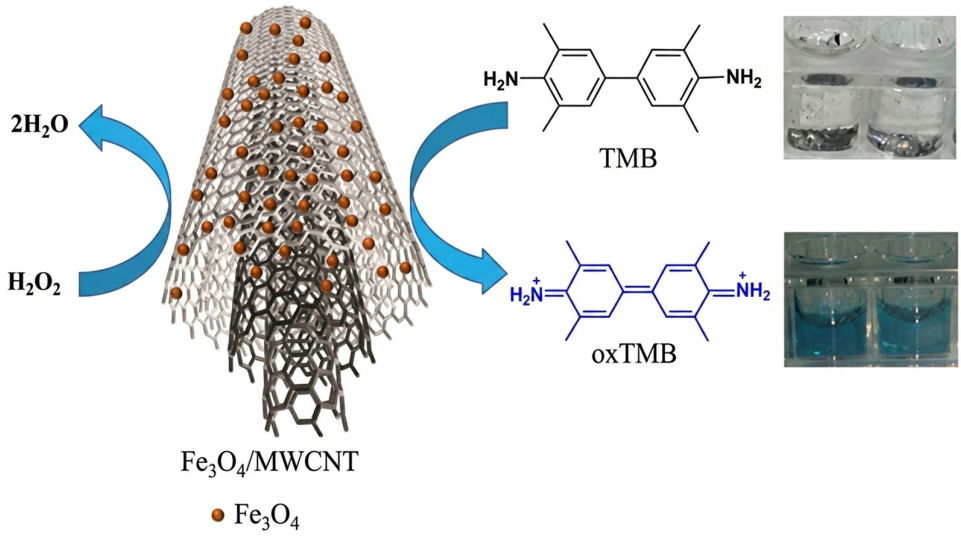

Figure 1. The process of co- procedure for the creation and characterisation of a carbon-based magnetic nanostructure: Peroxidase-like activity assay using 3,3-,5,5-tetramethylbenzidine reproduced from [12].

There are other forms of peroxidase-like nanozymes. For example, manganese oxide nanosheets (MnO_2) have gained attention because of their larger surface area, oxidising ability, and ease of synthesis. The MnO_2 nanozymes can also catalyse under low conditions and can effectively degrade dyes, antibiotic compounds and microbial membranes present in wastewater [13].

(b) Catalase-Mimicking nanozymes

Catalase-like nanozymes can convert H_2O_2 into harmless water and molecular oxygen. This can be a valuable form of detoxifying/mitigating oxidative stress or stabilising systems that experience increased peroxides and reactive oxygen species (ROS). Cerium oxide (CeO_2) nanoparticles are examples of catalase-like nanozymes. They can scavenge ROS and catalyse. Decomposition of H_2O_2 without generating free radicals allows it to be a safe option in certain biomedical or environmental applications [8,14].

Also, platinum (Pt) and gold (Au) nanoparticles have been studied for both oxidase and catalase-like activities. Notably, Pt nanoparticles show an unusually high catalytic activity and can be beneficial in removing residual oxidants that are not broken down by wastewater treatment [15].

(c) Oxidase-like Nanozymes

Oxidase-like nanozymes catalyse the oxidation of substrates, using molecular oxygen (O_2) as an electron acceptor to produce either H_2O_2 or superoxide radicals ($O_2\bullet^-$). This property is particularly useful for antimicrobial activity and for pollutant oxidation. For example, carbon-based nanomaterials, including graphene oxide (GO) and carbon dots, were modified to exhibit oxidase-like activity, which has proven useful for degrading organic pollutants and disinfecting water [16].

Some nanozymes, like ceria and copper-based nanomaterials, may even simultaneously mimic multiple enzymes, performing peroxidase, oxidase, and catalase mimicking behaviour, depending on the substrate and conditions [17]. Such multifunctionality is desirable in water purification applications, which depend on a spectrum of oxidative pathways working together to oxidatively degrade complex mixtures of contaminants.

2.1.2. Hydrolase-Mimicking Nanozymes

Hydrolase-mimicking nanozymes are an important category of artificial enzymes that catalyse the hydrolysis of chemical bonds to mimic natural hydrolases, such as phosphatases, esterases, and proteases. Figure 2 shows the most common enzyme-mimicking activities of nanozymes. A breakdown occurs through the addition of water molecules (hydrolysis). Hydrolase-mimicking nanozymes are valuable for applying environmental aspects (for example, breaking down organophosphates, pesticides, nerve agents, and other hazardous materials) that are present in soil and water [9]. Metal–organic frameworks (MOFs) are one of the more prominent examples of hydrolase-mimicking nanozymes. MOFs can be synthesised so that it will provide phosphatase-like properties. For example, zirconium-based MOFs, such as UiO-66, have been shown to have significant catalytic activity for the separation of phosphate esters, which can be attributed to the strong Lewis acidity of Zr (IV) centre's and coordination flexibility provided by the ligands (Bůžek et al., 2018, [18]). In particular, these materials are studied for the degradation of organophosphorus pesticides, which are some of the most common contaminants in agricultural runoff and drinking sources in rural and disaster-affected areas [19]. Hydrolase-mimicking nanozymes provide many advantages, and there are many hydrolase-mimicking nanozymes that show exceptional stability to pH and temperature change and are reusable, which could drastically lower operational costs as compared to using natural enzymes. Further, these systems can be combined with oxidoreductase nanozymes to produce a multifunctional catalytic platform for use in comprehensive water treatment [9]. Nanozymes are becoming the focus of interest as the world moves towards the development of portable and field-deployable water purification systems for remote villages and emergency settings where advanced filtration and chemical treatment systems are not accessible.

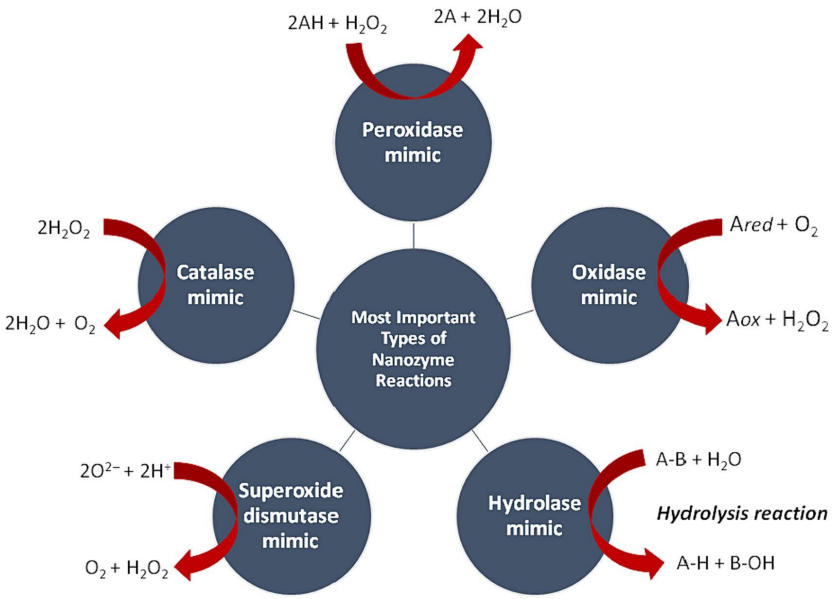

Figure 2. Most common enzyme-mimicking activities of nanozymes. Reproduced from [20].

2.1.3. Superoxide Dismutase (SOD)-like Nanozymes

Superoxide dismutase (SOD)-like nanozymes belong to a main class of oxidoreductase-mimicking nanomaterials that can catalyse the redox conversion of superoxide anions ($O_2\bullet^-$) to molecular oxygen (O_2) and hydrogen peroxide (H_2O_2). This catalytic action is like that of natural SOD enzymes, which are important for establishing and maintaining redox balance while also protecting biological and environmental systems from oxidative stress. The presence of superoxide radicals in water (e.g., from microbial metabolism, industrial

effluents, and photo-oxidation) can serve as an indicator of water degradation, which can contribute to toxicity and secondary pollutant formation, making their use in pollutant removal advantageous [10,11]. Cerium oxide nanoparticles (CeO_2 NPs) are among the most studied SOD-like nanozymes, and they are nanoparticles that can switch between the Ce^{3+} and Ce^{4+} oxidation states, and therefore can remove superoxide radicals in both their oxidation states. Additionally, oxidation states allow for redox cycling, so they can provide a longer-lasting catalytic performance [8]. In comparison to SOD-like nanozymes that are not considered redox-active and require methods to replace them. Furthermore, CeO_2 NPs exhibit multifunctionality, as they also mimic catalase and peroxidase catalytic activity, which can convert superoxide radicals to H_2O_2 and subsequently degrade H_2O_2 to harmless water and O_2, thus significantly reducing associated toxicity for remediation efforts. H_2O_2 to harmless water and oxygen, resulting in a redox-neutral catalytic cycle [8]. Another common material in this category includes manganese-based nanoparticles (ex., manganese oxide (Mn_3O_4) and MnO_2). Manganese nanoparticles have shown very strong SOD-like effects due to the facility of the redox interconversion between the Mn^{2+} and Mn^{3+}/Mn^{4+} states. Mn-based nanozymes with a large surface reactivity and environmental stability are an optimal approach for the removal of ROS from micro-polluted water, reducing cellular toxicity and protecting aquatic ecosystems [10]. Besides environmental uses, SOD-like nanozymes have also led to interest in their use for portable and fieldable water purification devices, applicable to resource-limited environments. These nanozymes, integrated into membranes, filters, or hybrid devices, could effectively neutralise oxidative reactions caused by reactive oxygen species in water systems, thereby improving the safety and quality of drinking water in rural areas and during emergencies. By utilising nanozymes based on function, such as peroxidase, oxidase, catalase, hydrolase, or SOD, researchers and engineers can create a system of multifunctional water purification systems corresponding to different contaminant types. SOD-like nanozymes are a major contribution to the general framework of water detoxification processes, especially in cases where oxidative pollutants or microbial pathogens are primary contributors to water contamination.

2.2. Advantages over Natural Enzymes

Nanozymes offer a range of outstanding benefits over natural enzymes, making them particularly suitable for inclusion in handheld and on-site water purification systems. Among all these benefits is its excellent performance stability: while natural enzymes are subject to thermal denaturation under extreme pH, temperature, or inhibitors, nanozymes possess notable catalytic activity that includes a wide range of environmental conditions, making them suitable for on-site or emergency use. Moreover, nanozymes are less expensive, due to lower production costs, easier mass synthesis, and longer shelf life, so that the practical aspects around enzyme storage and shipping are greatly reduced.

Additionally, nanozymes exhibit material and structural flexibility to be able to modify their catalytic activity via surface modifications, doping, or composites, unlike biological enzymes. This versatility lends itself to addressing a wide variety of waterborne contaminants, including pathogens, organic pollutants, and heavy metals, which are inherently incompatible with earlier biological techniques. Finally, nanozymes are fundamentally compatible with modern device formats, including microfluidic chips, point-of-care test kits, and nanocomposite membranes, which means they can be appropriately placed into next-generation, decentralised water purification technologies [6].

2.2.1. Improved Stability Under Extreme Conditions

Natural enzymes are highly sensitive biomolecules that can quickly lose their catalytic activity when exposed to non-physiological pH, high temperature, or organic solvents.

These instabilities interfere with their applications in outdoor and uncontrolled environments, for example, in rural villages or areas hit by disasters. On the other hand, due to their inorganic or composite nature, nanozymes often exhibit a high degree of thermal and chemical stability. Many nanozymes, including metal oxides, carbon-based nanostructures, and metal-organic frameworks, have been reported to retain full enzymatic activity over a wide pH range and at temperatures over 80 °C [21]. Given the functional stability of nanozymes, they can excel in water purification applications in harsh environmental conditions, for example, in flood zones, arid lands, or humanitarian situations.

2.2.2. Cost-Effectiveness and Simplicity of Manufacturing

Typically, the raw materials for nanozyme synthesis are numerous and inexpensive. Nanozyme synthesis uses raw materials such as metal salts, carbon derivatives, and polymers. Moreover, the synthesis methods are very simple and inexpensive and require little equipment and can be implemented in a scalable manner. This is very different to natural enzymes, which may require advanced purification from biological sources, expensive recombinant expression systems, and cold-chain storage. Thus, nanozyme-based purification platforms are a more cost-effective alternative to provide low-income communities.

2.2.3. Reusability and Longevity

Another key advantage is the longevity of nanozymes. Natural enzymes or isolates break down easily under storage, or sometimes after even a small number of uses. Nanozymes are typically stable for months or even years, often retaining high catalytic efficiency after many reaction cycles [21]. A strong and durable physicochemical structure allows for maximal reuse, which is beneficial not only for saving performance costs but also for minimising performance downtime in decentralised water treatment systems.

The physicochemical structure allows for maximal reuse, which is beneficial not only for saving operational costs but also for minimising operational downtime in decentralised water treatment systems.

2.2.4. Versatile Integration with Hybrid Platforms

Flexibility with Hybrid Systems Nanozymes can be fixed or inserted into several substrates, such as polymer membranes, silica gels, carbon nanotubes, and paper-based strips. Nanozymes can then be incorporated into tools, such as lateral flow assays, microfluidic chips, and multi-layer filtration cartridges [6]. Modular compatibility allows developers to create smaller and more portable user-friendly systems of purification with the ability to perform multi-step reactions (e.g., oxidation or hydrolysis) in a single operation. Hybrid systems are a great partner in remote locations that may have constraints on materials, space, resources, and expertise.

2.2.5. Broad Catalytic Functionality and Customizability

Nanozymes can be designed with broad catalytic capabilities, unlike natural enzymes, which are usually designed to perform a specific function on a specific substrate. Thus, nanozymes can be designed to give them multiple catalytic properties, such as peroxidase, oxidase, catalase, and hydrolase mimetics, all in one nanostructure. By utilising methods such as doping, surface modification, or creating composites, their selectivity and activity can be customised and varied for addressing specific contaminants. Specific contaminants handled by nanozymes include pesticides, pharmaceuticals, heavy metals, and microbial toxins [6]. This adapted function and the broad spectrum of pollution decrease potential are further balanced by the multifunctional benefit of their ability to co-exist with complex pollution matrices as they degrade contaminants containing heavy metals and pharmaceu-

ticals, while preventing and/or deactivating microbial contaminants, limiting whether a single enzyme would be effective for a target contaminant.

3. Role of Structural and Electronic Features in Nanozyme Catalysis

The availability, accessibility, and built-in reactivity of catalytically active sites are controlled by the physicochemical and electronic structures of nanozymes, which affect their catalytic performance. Particle size is one of the most important of these factors. The surface-to-volume ratio generally rises with decreasing particle size, exposing more active sites and increasing catalytic activity. However, aggregation, surface energy instability, and altered electronic states could negatively impact the catalytic durability and long-term performance of excessively tiny nanoparticles [6].

Nanozyme activity is also greatly affected by morphology and crystal structure. Different nanostructures, including nanospheres, nanorods, nanosheets, and hierarchical designs, exhibit unique atomic arrangements and crystallographic features that directly affect catalytic kinetics and adsorption behaviour [6]. For example, compared with isotropic particles, anisotropic nanostructures (such as nanorods or nanosheets) usually enable directed charge transport and improved reactant accessibility, thereby increasing catalytic performance [4,6,11,22]. For example, Zheng et al. [23] obtains hollow nanocages of $PdPt_3$ and $PdIr_3$ by etching core/shell Pd/Pt and Pd/Ir nanocubes. The hollow design featured a porous exterior enclosed by a thin frame, significantly enhancing their catalytic effectiveness for uricase breakdown and H_2O_2 removal in physiological settings. The cubic hollow $PdPt_3$ and $PdIr_3$ nanocages exhibited significant activity for self-cascade uricase/POD-like catalytic reactions [23]. In a separate study, Pt hollow nanodendrites were created by selectively eliminating Pd cores from Pd@Pt core–frame nanodendrites, demonstrating greater POD-like activity compared to Pd nanocubes and Pd@Pt core–frame nanodendrites [6]. The researchers indicated that the large specific area of the nanodendrite shells and the hollow structures with porous surfaces greatly improved the POD-like characteristics of the Pt hollow nanodendrites. Additionally, the morphology-dependent optical characteristics of plasmonic noble metals can also be synergistically incorporated into nanozymes. For example, Jia et al. created flower-shaped AgPd blackbody nanozymes, exhibiting strong LSPR absorption across a wide spectral range of 400 to 1300 nm [24,25]. A summary is shown in Figure 3.

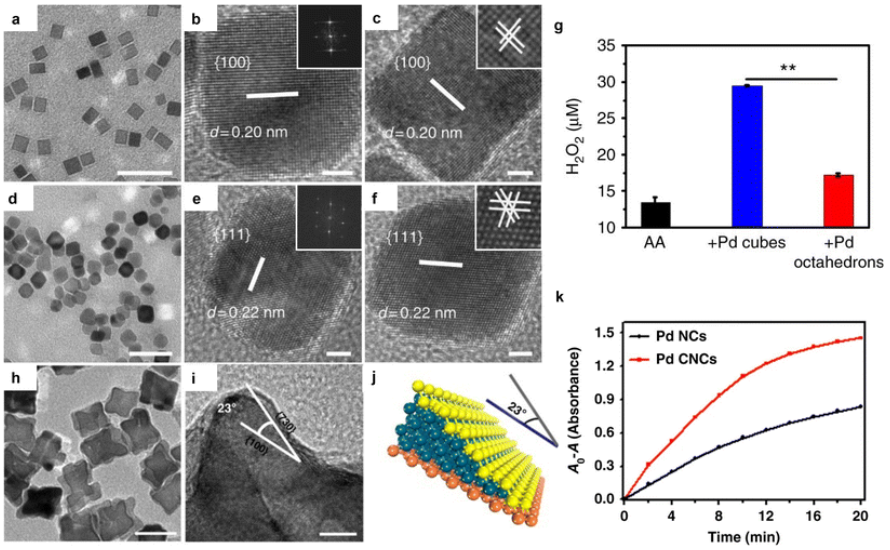

Figure 3. (**a**) TEM image (scale bar: 20 nm), (**b**,**c**) HRTEM images (scale bar: 2 nm), and corresponding fast Fourier transformation (FFT) pattern (inset) of (100)-faceted Pd cubes. (**d**) TEM image (scale bar:

20 nm), (**e**,**f**) HRTEM images (scale bar: 2 nm), and corresponding FFT pattern (inset) of (111)-faceted Pd octahedra. (**g**) Comparison of concentrations of H_2O_2 generated using different Pd nanozymes, showing a facet-dependent oxidase-like (OxD-like) activity. AA (ascorbic acid), as a physiologically relevant antioxidant, was used as substrate to assess the OxD-like activities of Pd nanocrystals. Reproduced with permission from Ref. [26]. Copyright 2018, Springer Nature Limited. (**h**) TEM image of (730)-faceted Pd concave nanocubes (Pd CNCs) (scale bar: 50 nm), (**i**) HRTEM image of Pd CNCs (scale bar: 5 nm), and (**j**) model of the atomic arrangement on the (730) surface of Pd CNCs. (**k**) Comparison of absorbance changes of substrate using Pd nanocubes (NCs) or Pd CNCs, showing a facet-dependent OxD-like activity. Reproduced from reference [27].

Defect engineering is also an effective approach for increasing nanozyme activity, especially when oxygen vacancies are introduced. To help produce reactive oxygen species (ROS), such as hydroxyl radicals (•OH) and superoxide radicals ($O_2\bullet^-$), oxygen vacancies serve as electron-rich sites that facilitate the adsorption and activation of molecular oxygen or hydrogen peroxide. These defect sites change reaction modes and selectivity in addition to speeding up catalytic reaction kinetics [28].

Also, the electronic structure of nanozymes, including charge distribution, oxidation states, and band structure, is important for controlling catalytic processes. Electron transfer efficiency and catalytic performance can be significantly improved by adjusting these electronic properties using techniques such as heteroatom doping, single-atom engineering, heterostructure creation, and surface functionalisation [29].

Overall, the logical design of high-performance nanozymes requires a thorough understanding of the structure–activity relationship. Nanozyme applications in environmental remediation, particularly water purification, can be advanced by optimising catalytic activity, stability, and selectivity through precise adjustment of characteristics like size, shape, defect density, and electronic structure.

4. Water Contaminants and the Need for Nanozyme-Based Treatment

Water contamination stems from both anthropogenic and natural sources, and can be divided into biological, chemical, and physical contaminants. Each form can harm the organisms that require water, ultimately impacting human health and the environment. The continued development of new treatment technologies, such as nanozyme systems, is essential.

- **Biological Contaminants**

Biological contaminants mainly consist of pathogenic microorganisms, such as bacteria, viruses, and protozoa. Pathogens enter water systems typically through faecal contamination from sewage treatment, runoff, and animal waste. Pathogens include many bacteria, such as *Escherichia coli* (*E. coli*), *Salmonella* spp., viruses such as enteroviruses, noroviruses, and hepatitis A virus and protozoa such as Giardia lamblia and *Cryptosporidium* parvum. Bacteria like *E. coli* and *Salmonella* spp., *Giardia* spp., and *Cryptosporidium* spp. are amongst the most frequently detected in drinking sources, and have been responsible for many drinking waterborne illness outbreaks in both humans and animals. Although many bacterial and protozoan pathogens cannot infect human hosts at fairly low infectious doses, they still can infect and cause illness in the host organism. Pathogens are of main concern for two reasons. First, viruses (like enteroviruses, noroviruses, and hepatitis A virus) rarely cause water-borne illness and are extremely rare in drinking water aquifers due their infectious nature, where illness can begin with as few as one or two virons, and they can resist many disinfection methods, which makes them more resistant contaminants. Secondly, biological contaminants not only have the potential to be harmful to human and animal health, but they can also make the treatment of water more complex through the formation of biofilms and their interaction with other contaminants [1].

- **Chemical Contaminants**

Chemical contaminants are a collection of different inorganic and organic chemicals originating from many industries, agricultural activities, and private industries. Heavy metals, such as arsenic (As), lead (Pb), mercury (Hg), cadmium (Cd), and chromium (Cr), are examples of non-biodegradable pollutants that can remain in the environment for hundreds of years. Additionally, these metals can be found in trace concentrations in drinking water, leading to adverse effects on the human body. Arsenic, for example, is linked to skin lesions, nerve damage, and an increased risk of cancer in various areas of South Asia and even parts of the US. Pesticide residues, including organophosphates, carbamates, and chlorinated hydrocarbons, are toxic substances that are deposited in water bodies through agricultural runoff. Pesticides have adverse effects on both human and aquatic organisms. Many unused or leftover pharmaceuticals can be found in surface and groundwaters, especially antibiotics, hormones, and analgesics, causing health concerns through increased antimicrobial resistance in humans, secondary effects on aquatic organisms, and endocrine disruption mechanisms in wildlife [3,20,30].

- **Physical contaminants**

Physical contaminants change the appearance, temperature, and suspended materials in water. Physical contaminants include turbidity (clarity), colour, taste, odour, and suspended solids. Suspended solids, including silt, clay, organic matter, and microplastics, can reduce the effectiveness of disinfection processes by shielding pathogens and absorbing disinfectant chemicals. Increasing turbidity not only reduces clarity but also facilitates the transport of microbial contaminants and harmful algal blooms (HABs). Furthermore, microplastics and nanoplastics are newer physical contaminants that are likely present in surface water and have unknown effects on ecosystems and public health due to their accumulation and persistence [31]. The coexistence of multiple contaminants poses a significant challenge for traditional water purification technologies [32]. Given these challenges, new technologies or approaches for water treatment, like using nanozymes, are starting to gain attention as a new promising consideration for tackling of complex and mixed contaminants [5,33]. Nanozymes are new approaches that complement high catalytic activity with a more multi-functional technology [11,34,35].

4.1. Role of Nanozymes in Addressing Water Contaminants

Nanozymes, nanomaterials that can mimic enzyme-like functions intrinsically, are poised to transform water purification through biological, chemical, and physical methods. Nanozymes can specifically act on a wide range of biological, chemical, and physical contaminants through catalytic mechanisms and can be incorporated into modular or multifunctional systems.

For example, nanozymes often exhibit multiple enzyme-like activities, including peroxidase-like, oxidase-like, catalase-like, and superoxide dismutase-like. These activities allow nanozymes to catalytically inactivate a broad spectrum of pathogenic microorganisms (bacteria, viruses, protozoa, etc.). For example, Fe_3O_4 nanozymes mimic peroxidase activity in a way that they catalyse hydrogen peroxide (H_2O_2) and lead to the production of reactive oxygen species (ROS) to make hydroxyl radicals (•OH). This process has strong antimicrobial activity due to hydroxyl radicals damaging cell membranes, proteins, and nucleic acids of microbes [7]. The significant value of nanozymes is that developing systems do not have some of the logistical and by-product issues associated with using traditional disinfectants like chlorine, which has a variety of contaminants to worry about and can form harmful disinfection by-products (DBPs) in treated waters, as well as reduced efficacy in turbid water. Nanozyme-based systems also have an advantage regarding operation: they can basically use/catalyse any oxidising reactivity for oxidants, and work at a wide range of

pH and temperature; thus, they can be used in remote/rural settings where environmental variability is nearly a range-day situation Stability and reusability also increase the benefits and lower the costs of disasters and clean water, and the need for chemical inputs as compared to rapidly degrading natural enzymes or disinfectant chemicals.

4.2. Catalytic Degradation of Chemical Pollutants

Besides microbial inactivation, nanozymes catalyse the breakdown of chemical contaminants like phenolic compounds, dyes, antibiotics, and heavy metals through redox reactions. Cerium oxide (CeO_2) nanozymes, for example, vary from Ce^{3+} to Ce^{4+} oxidation states for redox-mediated breakdown of organic pollutants and radical scavenging [8,36]. Manganese dioxide (MnO_2) nanozymes have also catalysed the breakdown of antibiotics like tetracycline and sulfamethoxazole through oxidation reactions, alleviating pharmaceutical contamination in wastewater [13]. Some nanozymes are also functionalised with ligand compounds or doped with other metals to increase their selectivity toward specific contaminants, like arsenic or lead, providing specific decontamination while maintaining the naturally occurring mineral concentration of the water.

4.3. Integration into Multifunctional Purification Platforms

At the core of nanozymes' power is their flexibility and their ability to integrate into next-generation multifunctional purification platforms. They can be integrated into:

- Membrane filters that dissolve pollutants through catalysis while filtering particulates;
- Hydrogel cartridges for point-of-use design faction in portable devices;
- Test strips or nanocomposite films for single-step detection and treatment based on paper;
- Solar or gravity-powered water purification units for disaster relief or remote villages.

The modular and multifunctional aspects of these innovations facilitate the removal of biological, chemical, or physical properties from water, whereas many of the traditional technologies have difficulty achieving this efficiently in one step. Figure 4 is showing the nanozyme based treatment of imaging contaminants in wastewater [37].

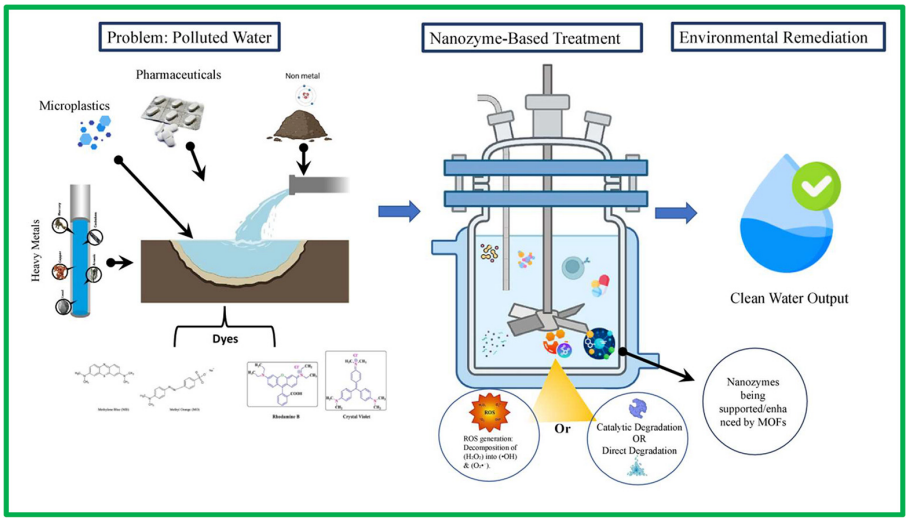

Figure 4. Illustrates the nanozyme-based treatment of emerging contaminants in wastewater. Reproduced from the reference [37].

Additionally, nanozyme systems can be designed at the microscale for personal water bottles or at the community scale as a filtration unit tailored to local needs, and they also add another level of flexibility to future water technologies. Collectively, nanozymes' attributes

make them an essential aspect of the future of water treatment technologies in addressing the numerous global issues surrounding water security. Conventional water treatment methods have made significant progress, but they still have several serious limitations that limit their ability to effectively address new and complex contaminants:

Inadequate pollution removal: Traditional methods mostly fail to completely break down long-term organic pollutants, resulting in the production of hazardous intermediate byproducts [38].

Low effectiveness against mixed contaminants: Many systems are designed to remove a single pollutant, but they perform poorly in actual wastewater that contains complex mixtures of organic, inorganic, and microbiological contaminants [32].

High energy and operating costs: Membrane filtration and advanced oxidation are examples of advanced processes that require significant energy input and maintenance [38,39].

5. Modes of Action in Nanozyme-Aided Purification

Nanozymes employ multiple physicochemical mechanisms that enable multifunctionality and the purification of water from biological and chemical contaminants. mainly, these modes of action rely on the production of reactive oxygen species (ROS), adsorption-catalysis coupling, and synergistic/cascade events that mimic multi-enzyme mechanisms in nature. Understanding these fundamentals is key to developing nanozyme systems that have high efficiency, specificity, and stability.

5.1. Reactions Similar to Fenton

In nanozyme systems, Fenton-like reactions are among the most widely studied catalytic routes, especially for iron- and transition-metal-based nanozymes. In these situations, hydrogen peroxide (H_2O_2) is broken down by metal ions (such as Fe^{2+}/Fe^{3+} and Cu^{+}/Cu^{2+}) to produce highly reactive hydroxyl radicals (•OH):

$$Fe_2{}^{+} + H_2O_2 \rightarrow Fe_3{}^{+} + \cdot OH + OH^{-}$$

By offering high-surface-area active sites and enabling rapid redox cycling between oxidation states, nanozymes improve this process. Nanozyme-based catalysts exhibit greater stability, reusability, and activity over a broader pH range than homogeneous Fenton systems [4,7,40]. In addition, advanced nanozyme designs (such as bimetallic systems and single-atom catalysts) can change the reaction pathway, promoting more efficient ROS production and reducing oxidant consumption.

5.2. Production of Reactive Oxygen Species (ROS)

One of the most important modes for purification utilised by nanozymes is the production of reactive oxygen species (ROS), which are very reactive molecules that oxidise and destroy various contaminants, such as pathogens and persistent organic pollutants [7]. Peroxidase, an example of a nanozyme (i.e., Fe_3O_4, V_2O_5, Co_3O_4) catalysis the decomposition of hydrogen peroxide (H_2O_2) to produce hydroxyl radicals (•OH), which are powerful oxidising agents that non-specifically oxidise bacterial membranes, nucleic acids, and chemical bonds contained in organic pollutants such as phenols, dyes, and antibiotics [4]. Oxidase-like nanozymes, like cerium oxide (CeO_2) or manganese oxide (Mn_3O_4), promote the direct reduction of oxygen to produce superoxide anions (O_2•–) or hydrogen peroxide without any added substrate [22,36]. This makes them suitable for substrate-free disinfection applications. The nanozymes' ROS production has been widely regarded as a suitable option for simultaneously disinfecting microbes and degrading pollutants [22].

5.3. Adsorption and Catalysis

In addition to catalytic oxidation, some nanozymes exhibit combined adsorption and catalytic degradation functions. Hybridisation increases the residence time of contaminants near the active sites of nanozymes, thereby enabling more efficient degradation of pollutants. For example, iron nanozymes (e.g., Fe–N–C composites, Fe_3O_4-coated carbon nanotubes) can adsorb contaminants, such as heavy metals or organic molecules. The combination of adsorption with catalytic function into nanozymes allows their overall purification performance, especially in low or trace concentrations [41].

This dual-mode mechanism is also ideal for polluted water bodies characterised by large volumes and low contaminant concentrations, where adsorption concentrates contaminants within nanozyme catalytic hotspots.

5.4. Synergistic Mechanisms (Cascade Reactions)

To enhance degradation efficiency, specificity, or selectivity, advanced nanozyme systems are increasingly designed to mimic natural enzymatic pathways, exploiting two or more enzymatically mimetic activities in sequence.

For example, multi-enzyme mimetic systems like Co–CeO_2 nanocomposites or core–shell Au@Pt nanozymes combine oxidase and peroxidase-like activities to create a self-supplied catalytic cycle; these nanozyme systems first generate H_2O_2, which they then decompose into reactive oxygen species (ROS) to degrade pollutants [42].

This sequential coupling of activities eliminates the need for external reagents (e.g., H_2O_2) and enables substrate-specific increases, especially in resource-limited environments. Such systems also allow for more precise control of reaction pathways and potentially produce fewer toxic by-products during degradation reactions. Cascade nanozyme systems improve purification by combining paired or complementary activities into a single nanostructure that shows the biochemical/universe pathways of nature.

5.5. Reaction Pathways and By-Product Formation (Critical Discussion)

Even though nanozyme-driven oxidation processes are highly effective, they often produce intermediate byproducts that may be more hazardous or persistent than the original molecules. Complex organic contaminants, such as colours and medications, are usually not mineralised directly to CO_2 and H_2O during ROS-mediated breakdown. Rather, they go through a sequential oxidation process that yields intermediates such as aromatic fragments, carboxylic acids, and aldehydes. Certain intermediates may have greater potential for bioaccumulation, toxicity, or mutagenicity. For example, research on Fenton-like systems has demonstrated that organic pollutants can produce partially oxidised aromatic compounds through incomplete degradation, necessitating further treatment stages [38,40]. Table 1 giving an insight into Nanozyme Materials, Catalytic Mimicry, and Their Ap-plications in Water Purification Systems.

Table 1. Overview of Nanozyme Materials, Enzyme Mimicry, and Water Purification Applications.

Nanozyme Material	Enzyme Mimicry	Water Purification Applications	Reference
Fe_3O_4 nanoparticles	Peroxidase	Catalytic degradation of organic dyes (methylene blue, rhodamine B) and bacterial inactivation via Fenton-like reactions	[7]
CeO_2 nanoparticles	Catalase/SOD	Reactive oxygen species (ROS) regulation and redox-mediated detoxification of heavy metals in aqueous systems	[36]

Table 1. *Cont.*

Nanozyme Material	Enzyme Mimicry	Water Purification Applications	Reference
Au@Pt core–shell nanoparticles	Multi-enzyme (oxidase + peroxidase)	Cascade degradation of organic dyes and microbial inactivation	[42]
Fe–N–C single-atom nanozymes	Peroxidase + Adsorptive	Catalytic degradation and adsorption of antibiotic residues	[41]
Zr-based MOFs (e.g., UiO-66-NH_2)	Multi-enzymatic mimicry	Wide range removal: dyes, pesticides, and pharmaceuticals	[43]
Carbon dots	Peroxidase	Colorimetric detection and oxidation of pesticides	[44]
Graphene oxide functionalised with Fe_3O_4	Peroxidase + Adsorption	Adsorptive removal and oxidation of bisphenol A and phenolic compounds	[45]
TiO_2-based nanozymes (photoactivated)	Peroxidase/Photocatalyst	Solar-assisted degradation of persistent organic pollutants and microbes	[46]
V_2O_5 nanowires	Haloperoxidase mimic	Oxidative removal of pharmaceutical residues (e.g., ibuprofen)	[47]

6. Challenges and Limitations of Nanozyme-Based Water Purification Systems

Nanozyme-based water filtration systems have gained popularity as possible alternatives to traditional treatment technologies due to their catalytic adaptability and durability. However, these systems are still in the early stages of development, and their widespread use is hampered by several key issues. The majority of reported efficiencies are derived from controlled laboratory conditions that do not reflect the complexity of real water matrices containing natural organic matter and competing ions, which can significantly reduce catalytic performance. This presents a significant challenge due to the lack of standardised evaluation protocols.

Furthermore, because the impacts of physicochemical parameters on catalytic efficiency are not fully established, a limited understanding of structure–activity connections limits the rational design of nanozymes. The lack of comparative evaluations with conventional technologies raises concerns about scalability and practical viability, notably regarding kinetics, cost, energy consumption, and long-term stability. Furthermore, because thorough life-cycle and risk assessments are lacking, possible environmental and health issues related to nanoparticle leakage, toxicity, and bioaccumulation remain inadequately addressed.

Long-term usability is further restricted by operational issues such as fouling, aggregation, and regeneration difficulties. Hybrid systems have been proposed to improve performance, but their synergistic advantages remain unclear and could add complexity. Furthermore, the lack of field-scale validation and low technology readiness level (TRL 2–4) underscores the disconnect between lab research and practical application. Cost, usability, and user acceptability are examples of socioeconomic factors crucial to adoption, especially in environments with limited resources. All things considered, nanozyme-based systems show promise but are still in their infancy, necessitating more study in the areas of standardisation, mechanistic understanding, techno-economic assessment, and environmental safety.

7. Design of Nanozyme-Based Portable Systems

Nanozyme-based water purification systems are beginning to be developed with portability, affordability, and accessibility considering users located in resource-poor, remote, or emergency conditions. The structural designs focus on using the catalytic potential of nanozymes interactively, allowing them an easy-to-use, low-maintenance, and scalable pu-

rification approach. The following are the main structural designs that have been reported or are in progress.

7.1. Structural Designs

7.1.1. Modular Filters: Replaceable Nanozyme Cartridges

A modular filter design consists of different cartridges comprised nanozymes for targeting specific pollutants (e.g., dyes, bacteria, heavy metals) that can be replaced and/or upgraded during use, with the user having to remove the complete unit from the filtration system—this is more possible for long-term use in poor resource areas or for extended use on-site. Modular nanozyme cartridges will show flexibility and sustainability to point-of-use water purification devices [48].

If, for instance, the cartridges included with the structure contained Fe_3O_4 or CuO nanozymes, these would degrade organic dyes, while other cartridges comprised of ceria-based particles could remove heavy metals or scavenge reactive oxygen species (ROS). Because the structure is compartmentalised, combination therapy can be misused using many nanozymes for more spectrum/catalytic functions [8,9].

7.1.2. Paper-Based Systems: Inexpensive, Disposable, Single Use

Nanozyme papers are a low-cost, biodegradable, and easily disposed of option for rapid water testing and treatment. Paper-based devices consist of cellulose or nitrocellulose-based matrices with built-in peroxidase-like nanozymes such as carbon dots, MnO_2, and Prussian blue nanoparticles. Paper-based nanozyme strips in a disposable format can provide real-time detection and treatment of waterborne contaminants [49].

These systems can visually detect contaminants via colorimetric changes and begin a catalytic degradation of pollutants [33]. The low cost and single-use nature of these devices make them best suited for field diagnostics and rapid response during events such as natural disasters and the more common outbreaks of waterborne diseases.

7.1.3. Hydrogel Membranes: System of Nanozymes with Passive Flow Filtration

Hydrogel membranes with nanozymes exhibit a flexible, semi-permeable, area-based structure that naturally absorbs and degrades waterborne contaminants via diffusion and gravity-driven flow. Membranes based on 'nanozyme' technology enable longer-term pollutant degradation compared to flow-through systems, and can operate passively and energy-free. Hydrogels include familiar materials such as alginate, polyacrylamide, or PVA, with catalytically active nanocomposites embedded or encapsulated [50]. For example, Fe–Mn oxide nanozymes encapsulated in an alginate gel can simultaneously adsorb and oxidise phenolic compounds and microorganisms at neutral pH. Since the release behaviour of nanozymes from the gel matrix is slow, the membrane can maintain its function over a relatively long period of time, and undergo partial replacement.

7.1.4. Lateral Flow and Bottle-Top Filters: Ideal for Remote and Emergency Use

Lateral flow platforms and bottle-top nanozyme filters are portable, single-user devices with no electricity or infrastructure. These nanozyme systems incorporate nanozymes within membranes or porous media that allow untreated water to flow through via gravity or suction.

Devices can use $NiCo_2O_4$, CeO_2, or nanozyme bimetallic to remove bacterial pathogens and organic pollutants in one step. Some systems are also coupled to solar-activated photocatalysts to improve purification outdoors [51]. Due to their compact size and ease of use, these formats serve emergency kits, military deployments, and humanitarian response situations. Bottle-top and lateral-flow nanozyme filters "offer decentralised

water treatment options to populations that have either been displaced or do not have access to large-scale central purification systems" [52].

7.2. Integration with Other Technologies

To improve the overall performance, flexibility, and sustainability of nanoparticle-based portable water purification systems, researchers are increasingly including nanozymes with complementary technologies. These hybrid systems are designed to expand the range of contaminants removed, improve energy efficiency, and allow for deployment in remote areas, especially in remote locations during a disaster or underserved locations. The integrations of nanozymes with solar-driven photocatalysis, activated carbon/nanozyme hybrids, and battery-free.

7.2.1. Solar-Driven Photocatalysis

Solar energy is practically unlimited, renewable, and environmentally friendly, making it a legitimate energy source that can be coupled with a nanozyme platform for the photocatalytic degradation of pollutants. In photocatalytic processes, photoactive nanozymes, or photocatalyst–nanozyme composite materials, utilise sunlight as an energy source to enhance the formation of ROS (reactive oxygen species), thereby accelerating and improving the degradation of organic compounds, including pesticides, pharmaceutical contaminants, and dyes.

7.2.2. Hybrid Systems of Activated Carbon/Nanozyme

Activated carbon (AC) has proven effective for water treatment and is readily usable due to its large surface area and strong adsorption properties, especially against heavy metals, pharmaceutical residues, and endocrine disruptors. Despite its positive attributes, AC is not a catalytic material and is therefore limited in degrading biochar pollutants. Activated carbon-nanozyme hybrids allow for both adsorption and degradation of poor biodegradable, harmful pollutants in small, compact systems [53].

To utilise the adsorptive properties of AC while leveraging the catalytic activity of nanozymes, researchers have developed hybrid materials combining AC and nanozymes. In the hybrid materials, pollutants are first adsorbed into the AC matrix, and then subsequently degraded in situ through catalysis from the integrated nanozymes from materials such as MnO_2, CuO, and Prussian Blue nanoparticles.

For example, a MnO_2/activated carbon nanocomposite filter was shown to remove residual antibiotics such as ciprofloxacin and sulfamethoxazole, while simultaneously degrading those same contaminants, and thus, avoiding residual waste production [54]. This means filters should have to be regenerated rarely, and filters can last longer before being disposed of.

7.3. Case Studies

Both real-world and experimental applications of nanozyme-based systems demonstrate their unique ability to provide rapid, cost-effective, and decentralised water purification in emergency and rural settings. The following case studies show that through innovative integrations of materials, high-efficiency pollutant removal platforms can be developed.

7.3.1. Case Study 1: Flexible Fe-MOF Nanozyme Fibre Composites for Point-of-Use Water Disinfection

This case study involves the development of flexible fibre-based composite materials built in with Fe-MOF (iron–metal organic framework) nanozymes for rapid, on-site use water disinfection. In this work, Fe-MOF nanozymes with strong peroxidase-like catalytic

activity were fixed within a porous polymeric fibre matrix, creating a mechanically stable and reusable disinfection module.

When exposed to bacterially contaminated water containing *Escherichia coli* (~10^6 CFU mL^{-1}), the nanozyme–fibre composites achieved >99.99% inactivation within 10–15 min under room temperature. The disinfection mechanism depends on in situ catalytic decomposition of trace H_2O_2 into hydroxyl radicals (•OH), which induces simple oxidative stress, lipid peroxidation, and eventual rupture of bacterial cell membranes. On the other hand, the fibrous structure allows passive water flow and physical bacterial interception, enhancing contact efficiency between pathogens and reactive sites [55].

Mainly, the composite functioned without external energy input, pumps, or pressurisation, making it highly suitable for decentralised or emergency water treatment cases. Ageing studies further showed that the nanozyme composites maintained antibacterial activity after several months of storage at room temperature, highlighting their practicality for field deployment.

Due to their low material cost, flexibility, and scalable fabrication, these Fe-MOF nanozyme fibre composites were introduced as suitable for portable POU water purification systems in rural regions, disaster relief operations, and onsite sanitation.

7.3.2. Case Study 2: Fe_3O_4-Based Filters for Arsenic and Bacteria Removal in Disaster Camps

In another study, focused on emergency humanitarian deployments, a group of researchers developed a portable Fe_3O_4 nanozyme-based filtration apparatus with a handheld pump to treat arsenic-contaminated groundwater and microbial pathogens. Fe_3O_4 nanoparticles, which behaved like peroxidase enzymes, catalysed Fenton-like reactions to produce hydroxyl radicals that degraded organic contaminants and inactivated bacteria.

Also, the adsorption capacity for removing arsenic (As(V)) from water at 3 ppm concentration was investigated by atomic absorption spectroscopy. Results showed that the As(V) adsorption capacity of Fe_3O_4 was dependent on particle size. The maximum absorption efficiency (Hmax) was 99.02%, the equilibrium time was 30 min, and the maximum Langmuir isotherm adsorption capacity was 14.46 mg/g with Fe_3O_4 nanoparticles having an average size of 5 nm. The results indicate that reducing the size of Fe_3O_4 nanoparticles is a promising approach for removing As(V) ions from water and wastewater [56].

Highly, the appropriate situation for this apparatus is operated without electricity while using only manual pumping to push water through the nanozyme bed, providing an effective battery-free, portable, field usable system in disaster relief efforts, where reliable infrastructure may be destroyed.

8. Effect of Real Water Matrices on Nanozyme Performance

The complex structure of actual water matrices, including suspended particles, inorganic ions, and natural organic matter (NOM), significantly affects the efficiency of nanozyme-based water purification systems. These components can hinder catalytic reactions, especially those involving reactive oxygen species (ROS), thereby lowering therapy effectiveness and restricting its usefulness.

8.1. Natural Organic Matter (NOM) Scavenges ROS

Natural water systems are full of natural organic matter (NOM), which is made up of fulvic acids, humic compounds, and other organic macromolecules. Although NOM has two functions, its primary function is to scavenge reactive oxygen species, particularly hydroxyl radicals (•OH) and sulphate radicals (SO_4•$^-$). NOM dramatically lowers oxidation efficiency by competing with target contaminants for ROS.

NOM can also delay light penetration (in photocatalytic systems) and disrupt electron-transfer processes. The reaction rate constants between NOM and •OH are frequently equal to or greater than those of target pollutants.

By consuming ROS before they react with contaminants, NOM can significantly inhibit degradation rates, as demonstrated by advanced oxidation experiments, hence lowering overall treatment performance [57,58].

8.2. Inorganic Ion Interference (Cl^-, SO_4^{2-})

Common inorganic anions in water, such as sulphate (SO_4^{2-}) and chloride (Cl^-), can significantly alter the catalytic pathways of nanozymes. Ions of chloride (Cl^-): Create less reactive chlorine radicals (Cl•, Cl_2•$^-$) by reacting with hydroxyl radicals (•OH). Because of their lower oxidation potential, these secondary radicals exhibit lower degradation efficiency. may result in the production of chlorinated byproducts, raising questions about their toxicity. Ions of sulphate (SO_4^{2-}): In systems based on sulphate radicals, they compete with activation processes and affect how radical and non-radical pathways are balanced. act as scavengers or alter the ion strength, which can affect catalyst surface contacts.

In general, these ions can introduce unwanted side reactions, alter reaction pathways, and reduce the availability of ROS [59,60].

8.3. Turbidity and Particulate Impacts

Turbidity, caused by suspended solids and colloidal particles, introduces additional physical and chemical obstacles. Surface blocking: By attaching to nanozyme surfaces, particles can obscure their active sites and reduce catalytic activity. Limitations on mass transfer: Higher turbidity prevents contaminants and oxidants from diffusing to active sites. Light attenuation: Turbidity limits ROS production in photocatalytic nanozyme systems by reducing light penetration. Together, these impacts result in decreased overall efficiency and reaction kinetics, especially in untreated or highly contaminated water sources [1,2,35].

8.4. System Complexity and Combined Matrix Effects

In the real world, these elements work together to create extremely complex situations rather than acting independently: NOM + ions → increased competitive reactions and ROS scavenging Turbidity + NOM → a combination of chemical and physical inhibition Unpredictable catalytic activity in multi-component systems, because of this, nanozyme performance in the lab frequently overestimates real-world efficiency, which emphasises the necessity of testing in practical settings. The performance of various nanozyme-based systems for water treatment has been comparatively evaluated (Table 2).

Table 2. Comparative Performance of Representative Nanozyme-Based Systems for Water Treatment.

Nanozyme System	Target Contaminant	Performance (Reported)	Typical Time Scale	System Notes	Reference
Fe_3O_4 nanozyme (peroxidase-like)	H_2O_2/chromogenic substrates (TMB model system)	High catalytic activity (benchmark nanozyme system)	Minutes	Model system widely used to demonstrate activity (not direct pollutant removal)	[7]
CeO_2 nanoparticles	*E. coli*, oxidative stress systems	Significant antibacterial activity via ROS modulation	Minutes–hours	Redox cycling (Ce^{3+}/Ce^{4+}) governs activity	[36]
Fe-based Fenton-like nanozymes	Organic dyes (e.g., methylene blue, rhodamine B)	Typically >80% degradation under optimised conditions	30–120 min	Strong pH dependence and H_2O_2 requirement	[40]

Table 2. *Cont.*

Nanozyme System	Target Contaminant	Performance (Reported)	Typical Time Scale	System Notes	Reference
MOF-derived nanozymes	Antibiotics/organic pollutants	High catalytic degradation efficiency reported	30–120 min	High surface area and tunable active sites	[61]
Carbon-based nanozymes (graphene, doped carbon)	Phenols, dyes	Moderate to high degradation efficiency	40–120 min	Metal-free catalysis; stability advantage	[16]
Nanozyme systems in real water matrices	Mixed pollutants	Reduced efficiency due to NOM and ions	Longer treatment times	Matrix effects significantly influence performance	[58]

9. Applications in Villages and Emergency Scenarios

9.1. Rural Settings

Due to a lack of piped water supply systems or central municipal water treatment facilities, there can be significant challenges in ensuring clean, safe drinking water. Communities in rural and remote areas are constrained by the need for large capital investments, trained operators, and the electricity required by traditional water treatment plants, which are often unavailable to residents. Furthermore, nanozyme-based water purification systems provide decentralised low maintenance options that can be used in households or in communities [1,62].

Producing nanozymes is cheap, especially nanozymes that use abundant, inexpensive materials like iron oxide, cerium oxide, and manganese oxides. Nanozymes offer a robust platform for local production and deployment through small-scale manufacturing units [16]. In addition, nanozyme-based devices exhibit natural stability to variations in environmental conditions, such as temperature, pH, and turbidity, which are common in untreated rural water supplies, including ponds, rivers, and bore wells. Unlike natural enzymes, nanozymes remain stable under harsh conditions, enabling long-term, consistent performance across diverse environments. Moreover, their catalytic efficiency, combined with their chemical durability, allows them to remain active even under conditions that change, such as high hardness or organic load [4].

9.2. Emergency and Disaster Zones

Access to safe drinking water will always remain a main focus in emergencies, like floods, earthquakes, and conflict. Existing water treatment technologies cannot be applied due to practical and infrastructural limitations. Nanozyme-based purification systems, particularly those designed in small-scale and modular formats, have the potential to be applied and activated, with limited set-up time, on-site and in the field [21]. These systems, in most cases, do not require electrical power because they rely on gravity-fed filtration or manual pumping, making them ideal for use in water-stressed areas without power grid access.

The main benefits also include lightweight, shelf-stable nanozyme cartridges that can be transported in bulk to affected areas. These cartridges are active for long periods because nanozymes can be stored in the solid state (considered an inorganic substance), kept at room temperature, and still maintain catalytic activity for extended periods. This is a significant advantage over biological enzymes that must be maintained [48].

Also, its design will allow relief workers to increase the purification capability based on the size of the affected population. Whether used in refugee camps, mobile medical units, or field kitchens, these systems provide a scalable, reliable solution for on-site water treatment.

10. Environmental Toxicity and Life Cycle Assessment (LCA) of Nanozyme Systems

Although nanozyme-based systems offer many benefits for water purification, serious concerns remain about the harm they pose to human health and the environment. To ensure safe and sustainable use, problems such as bioaccumulation, ROS-induced toxicity, nanoparticle leaching, and incomplete life-cycle assessment (LCA) must be systematically assessed.

10.1. Environmental Release and Leaching of Nanoparticles

Leaching of metal ions or nanoparticles into treated water and adjacent surroundings is one of the main issues with nanozyme deployment. During catalytic cycles, nanozymes, especially those based on metals (e.g., Fe, Cu, and Mn), may release dissolved ions. Environmental factors that may accelerate structural deterioration and leaching include pH, ionic strength, and redox conditions. Exposure concerns can be increased by leached nanoparticles migrating into soil and aquatic systems. Such uncontrolled release raises concerns regarding secondary contamination, potentially offsetting the benefits of pollutant removal [63].

10.2. Bioaccumulation and Ecotoxicological Risks

There are serious concerns about the long-term ecological effects of nanoparticles introduced into the ecosystem, as they can undergo trophic transfer and bioaccumulate. Even at low concentrations, bacteria, plants, and aquatic species can adsorb or internalise nanozymes, potentially leading to accumulation in biological tissues and long-term damage.

Additionally, nanoparticles can move from primary producers to higher trophic levels in food chains, raising the possibility of exposure across an ecosystem. Although the degree of biomagnification varies, experimental data demonstrate that metal-based nanoparticles can experience trophic transfer in aquatic systems [64,65]. Crucially, although the potential dangers of bioaccumulation are widely acknowledged, there remain many unknowns about the long-term environmental fate, transformation processes, and actual biomagnification behaviour under practical conditions. To adequately assess ecological concerns and enable safe nanozyme deployment, this gap underscores the need for multi-trophic, long-term research [63,66].

10.3. Reactive Oxygen Species (ROS)-Induced Toxicity

In environmental applications, ROS production is a double-edged sword, even though it is essential to nanozyme catalytic activity. Overproduction of ROS (such as •OH and $O_2\bullet^-$) can overwhelm natural antioxidant defence systems in non-target organisms, leading to oxidative stress. Increased ROS levels can cause cytotoxicity, genotoxicity, and inflammatory responses by damaging vital cellular components, including lipids (membrane peroxidation), proteins (enzyme inactivation), and DNA (strand breaks and mutations). In aquatic habitats, where ongoing exposure may cause long-term, sub-lethal biological harm, these consequences are especially worrisome. Crucially, ROS-mediated toxicity can impact aquatic creatures, alter beneficial microbial communities, and harm wastewater treatment microbiota, all of which can upset ecological equilibrium [28,64].

Importantly, ROS-mediated toxicity can disrupt ecological balance by affecting aquatic life, changing beneficial microbial populations, and damaging wastewater treatment microbiota.

The Technology Readiness Level (TRL) system has been used to determine the maturity of nanozyme-based water filtration systems (Table 3). According to available data, the majority of systems remain at TRL 2–5, corresponding to early-stage prototypes and laboratory validation, with very few studies reporting field-level implementation. This shows a substantial disconnect between experimental research and practical implementation.

Table 3. Technology Readiness Levels (TRL) of Nanozyme-Based Water Purification Systems.

TRL Level	Stage Description	Nanozyme-Based System Status	Representative Examples (with References)
TRL 1–2	Basic principles observed	Fundamental studies on enzyme-like activity	Discovery of peroxidase-like activity of Fe_3O_4 nanozymes [7]
TRL 3	Proof-of-concept	Lab-scale pollutant degradation and disinfection	Nanozyme-mediated dye degradation and antibacterial activity in controlled systems [67]
TRL 5	Validation in the relevant environment	Testing under simulated real water conditions	Performance in the presence of NOM and ions [58]
TRL 7	System prototype in field conditions	Limited real-world deployment	Pilot-scale nanomaterial-based water purification systems [68]
TRL 8	The system is complete and qualified	Optimisation, durability, and safety validation	Stability and reuse studies of nanozyme systems [69]
TRL 9	Commercial deployment	Fully operational real-world systems	Limited commercialisation; nanozyme systems are still emerging compared to conventional technologies [70]

11. Techno-Economic Analysis of Nanozyme-Based Systems

The techno-economic sustainability of nanozyme-based water filtration technologies has a significant impact on their widespread adoption, particularly compared with conventional treatment techniques. Material synthesis and system integration account for a significant portion of the cost of nanozyme systems from a capital expenditure (CAPEX) standpoint. expensive-purity precursors, regulated synthesis conditions, and substantial energy input are frequently needed for advanced nanozymes, such as single-atom catalysts, doped nanostructures, and heterostructured materials, which can result in comparatively high starting prices. Capital investment is further increased by incorporation with useful systems, such as reactors or immobilisation supports.

There are significant financial trade-offs as compared to traditional technology. Despite concerns about hazardous disinfection byproducts, chlorination, one of the most widely used disinfection techniques, remains very appealing due to its low CAPEX and OPEX, ease of operation, and scalability. Membrane-based solutions, on the other hand, offer high removal efficiency but incur significant capital and operating expenses, mainly due to fouling control, energy requirements, and membrane manufacturing. Although nanozyme systems offer high catalytic performance and multifunctionality, they currently face higher synthesis costs and limited economic optimisation compared to known approaches.

The absence of thorough techno-economic evaluations under practical working situations is a crucial research gap. The majority of research concentrates on catalytic efficiency at the laboratory scale, giving little thought to long-term operating costs, scalability, and cost-performance connections. Developing low-cost synthesis techniques, enhancing catalyst durability, reducing reliance on external chemical inputs, and conducting rigorous economic benchmarking against traditional technologies are all necessary to address these issues. The development of nanozyme systems from lab-scale inventions to commercially viable water treatment solutions remains limited in the absence of such initiatives [71].

12. Future Prospects

The development of nanozyme-based portable water purification systems may offer a brighter future for innovative solutions to water issues worldwide, particularly in under-resourced rural regions and during emergencies. Innovations are being made in four areas: material sustainability, system intelligence, predictive designs, and deployment frameworks.

12.1. Biocompatible and Green Nanozymes

In light of recent developments, future nanozyme research should focus on developing biocompatible, green nanozymes, especially for water purification systems intended for human consumption. Conventional nanozymes are catalytically active but are often made with transition metals or synthetic materials that could be harmful to the environment or human health. Therefore, research into green nanozymes developed from plant extracts or biodegradable polymeric carriers is underway, as these nanozymes have low toxicity and are environmentally compatible [72].

Recently, it has been shown that nanozymes of iron oxide, cerium oxide, and zinc oxide can be synthesised by mediation by plant sources such as biomolecules of green tea, neem, or aloe vera since these phytochemicals have both reducing and ability to control which create a variety of materials that are catalytically active and have antimicrobial properties while also being biodegradable In addition, research with chitosan, cellulose, and other bio-materials has enabled encapsulation of nanozymes as particles or membranes that can be water-purified after usage and ultimately degrade in the environment [73].

12.2. Smart Responsive Systems

The incorporation of stimulus-responsive behaviours into nanozyme platforms is a forward-looking design that may improve specificity and efficiency in water cleaning. Smart nanozyme systems are designed to activate or enhance catalytic activity in response to various environmental conditions, including pH, redox potential, and the presence of specific contaminants. For example, peroxidase-like nanozymes can be designed to function only in acidic pH, which is often reflective of contaminated waters or waters with a high presence of pathogens. Next-generation nanozyme composites have been developed with molecular gates that detect lead, arsenic, or microbial toxins and alter their configuration electronically or structurally, enabling the degradation of these pollutants [34].

12.3. AI-Guided Nanozyme Design

Artificial intelligence (AI) and machine learning (ML) are rapidly evolving into invaluable tools for the design and discovery of nanozymes. Because nanomaterials have a large design space (size, shape, doping level, surface chemistry. AI-based predictive models can allow scientists to simulate the activity of a nanozyme material or evaluate multiple candidates based on properties such as catalytic efficiency, stability, and reusability, before the nanozymes are ever synthesised [74].

For example, ML algorithms can be used to estimate enzyme-like kinetics (including Michaelis–Menten parameters) from structural and compositional inputs, thereby rapidly prototyping nanozymes to remove specific contaminants from water, including nitrates, heavy metals, and organic pollutants. AI capability can also be used to improve formulation stability under varied environmental conditions for long-term use in portable systems [74].

12.4. Community-Based Deployment Models

Beyond technological innovation, the future success of nanozyme-based water purification also depends on scalable and community-centred application models. Integration with non-governmental organisations (NGOs), public health missions, and local governance structures can increase deployment in the affected area. Community-based systems highlights involving people, ownership, maintenance, training, and behavioural change factors that are often neglected in top-down approaches [70,75,76].

For example, some pilot studies in sub-Saharan Africa and Southeast Asia have successfully deployed modular nanozyme water filters through collaborations with health clinics and women-led cooperatives. These programs not only addressed water insecurity

but also promoted health education, local entrepreneurship, and stability [77]. Future directions may also include blockchain-based inventory tracking, real-time usage monitoring through IoT sensors, and mobile-based support platforms for maintenance guidance.

13. Conclusions

One potential way to address global barriers to safe drinking water is with nanozyme-based portable water purification systems. These systems use the catalytic activity of nanozymes to deactivate both biological and chemical contaminants, delivering effective performance and, in some cases, even reliable performance across a variety of environmental conditions, while also serving rural and emergency settings without water treatment infrastructure. These systems have advantages, such as high stability, long shelf-life, and low production costs, and are well-suited for decentralised, field-deployable platforms. In addition, the development of biocompatible, environmentally sustainable nanozymes would also address sustainability and public health considerations. In the future, innovative applications based on intelligent systems and stimulus-responsive designs, with AI-driven material design, will improve material performance, enhance selectivity, and reduce resource use. Along with showing how technologies are integrated into community-level deployment, public health strategies and local allies' involvement are also key elements, but this would be demonstrated by combining with public health resources. To conclude, nanozyme-based purification platforms offer a modern, community-based approach to improving access to safe water. With systematic research and real-world outcomes, nanozymes and nanozyme-based systems will surely transform the global trend toward access to safe, clean water.

Author Contributions: Conceptualization, N.C. and M.S.S.; methodology, M.S.S. and N.K.; software, N.C.; validation, M.S.S., K.K.A. and H.A.Q.; formal analysis, G.A.; investigation, N.C. and R.K.; resources, R.K. and N.K.; data curation, G.A. and B.Y.; writing—original draft preparation, N.C.; writing—review and editing, M.S.S., G.A., K.K.A. and H.A.Q.; visualization, B.Y.; supervision, M.S.S. and H.A.Q.; project administration, M.S.S.; funding acquisition, H.A.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Kristanti, R.A.; Hadibarata, T.; Syafrudin, M.; Yılmaz, M.; Abdullah, S. Microbiological Contaminants in Drinking Water: Current Status and Challenges. *Water Air Soil Pollut.* **2022**, *233*, 299. [CrossRef]
2. Loo, S.-L.; Fane, A.G.; Krantz, W.B.; Lim, T.-T. Emergency water supply: A review of potential technologies and selection criteria. *Water Res.* **2012**, *46*, 3125–3151. [CrossRef] [PubMed]
3. Wang, H.; Gao, X.; Zuo, Y. Research and Application of Water Treatment Technologies for Emerging Contaminants (ECs): A Pathway to Solving Water Environment Challenges. *Water* **2024**, *16*, 1837. [CrossRef]
4. Wei, H.; Wang, E. Nanomaterials with Enzyme-like Characteristics (Nanozymes): Next-Generation Artificial Enzymes. *Chem. Soc. Rev.* **2013**, *42*, 6060–6093. [CrossRef] [PubMed]
5. Singh, R.; Umapathi, A.; Patel, G.; Patra, C.; Malik, U.; Bhargava, S.K.; Daima, H.K. Nanozyme-based pollutant sensing and environmental treatment: Trends, challenges, and perspectives. *Sci. Total. Environ.* **2022**, *854*, 158771. [CrossRef] [PubMed]
6. Wu, J.; Wang, X.; Wang, Q.; Lou, Z.; Li, S.; Zhu, Y.; Qin, L.; Wei, H. Nanomaterials with enzyme-like characteristics (nanozymes): Next-generation artificial enzymes (II). *Chem. Soc. Rev.* **2018**, *48*, 1004–1076. [CrossRef]
7. Gao, L.; Zhuang, J.; Nie, L.; Zhang, J.; Zhang, Y.; Gu, N.; Wang, T.; Feng, J.; Yang, D.; Perrett, S.; et al. Intrinsic peroxidase-like activity of ferromagnetic nanoparticles. *Nat. Nanotechnol.* **2007**, *2*, 577–583. [CrossRef] [PubMed]

8. Xu, C.; Qu, X. Cerium oxide nanoparticle: A remarkably versatile rare earth nanomaterial for biological applications. *NPG Asia Mater.* **2014**, *6*, e90. [CrossRef]
9. Liao, X.; Wang, X.; Li, B.; Wang, L.; Chen, Y. Hydrolytic nanozymes: Classification, activity regulation, and applications in sensing and degradation of environmental pollutants. *Coord. Chem. Rev.* **2025**, *541*, 216807. [CrossRef]
10. Zhao, H.; Zhang, R.; Yan, X.; Fan, K. Superoxide dismutase nanozymes: An emerging star for anti-oxidation. *J. Mater. Chem. B* **2021**, *9*, 6939–6957. [CrossRef] [PubMed]
11. Nagendran, V.; Goveas, L.C.; Vinayagam, R.; Varadavenkatesan, T.; Selvaraj, R. Nanozymes in environmental remediation: A bibliometric and comprehensive review of their oxidoreductase-mimicking capabilities. *Microchem. J.* **2024**, *207*, 111748. [CrossRef]
12. Salarizadeh, N.; Sadri, M. Preparation and characterization of a carbon-based magnetic nanostructure via co-precipitation method: Peroxidase-like activity assay with 3,3′,5,5′-tetramethylbenzidine. *Nanomed. Res. J.* **2017**, *2*, 150–157. [CrossRef]
13. Ishfaq, A.; Shahid, M.; Nawaz, M.; Ibrar, D.; Hussain, S.; Shahzad, T.; Mahmood, F.; Rais, A.; Gul, S.; Gaafar, A.-R.Z.; et al. Remediation of wastewater by biosynthesized manganese oxide nanoparticles and its effects on development of wheat seedlings. *Front. Plant Sci.* **2023**, *14*, 1263813. [CrossRef] [PubMed]
14. Thao, N.T.M.; Do, H.D.K.; Nam, N.N.; Tran, N.K.S.; Dan, T.T.; Trinh, K.T.L. Antioxidant Nanozymes: Mechanisms, Activity Manipulation, and Applications. *Micromachines* **2023**, *14*, 1017. [CrossRef] [PubMed]
15. Cheng, Q.; Yang, Y.; Peng, Y.; Liu, M. Pt Nanoparticles with High Oxidase-Like Activity and Reusability for Detection of Ascorbic Acid. *Nanomaterials* **2020**, *10*, 1015. [CrossRef] [PubMed]
16. Das, A.; Uppaluri, R.V.; Mitra, S. A review on waste derived carbon nanozyme: An emerging catalytic material for monitoring and degrading environmental pollutants. *Chem. Eng. J.* **2025**, *507*, 160762. [CrossRef]
17. Jiang, P.; Zhang, L.; Liu, X.; Ye, C.; Zhu, P.; Tan, T.; Wang, D.; Wang, Y. Tuning oxidant and antioxidant activities of ceria by anchoring copper single-site for antibacterial application. *Nat. Commun.* **2024**, *15*, 1010. [CrossRef] [PubMed]
18. Bůžek, D.; Demel, J.; Lang, K. Zirconium Metal–Organic Framework UiO-66: Stability in an Aqueous Environment and Its Relevance for Organophosphate Degradation. *Inorg. Chem.* **2018**, *57*, 14290–14297. [CrossRef] [PubMed]
19. Jiang, L.; Huang, T.; Feng, S.; Wang, J. Zirconium(IV) functionalized magnetic nanocomposites for extraction of organophosphorus pesticides from environmental water samples. *J. Chromatogr. A* **2016**, *1456*, 49–57. [CrossRef] [PubMed]
20. Sen, A.; Oswalia, J.; Yadav, S.; Vachher, M.; Nigam, A. Recent trends in nanozyme research and their potential therapeutic applications. *Curr. Res. Biotechnol.* **2024**, *7*, 100205. [CrossRef]
21. Ashrafi, A.M.; Bytesnikova, Z.; Barek, J.; Richtera, L.; Adam, V. A critical comparison of natural enzymes and nanozymes in biosensing and bioassays. *Biosens. Bioelectron.* **2021**, *192*, 113494. [CrossRef] [PubMed]
22. Lin, Z.; Yuan, J.; Niu, L.; Zhang, Y.; Zhang, X.; Wang, M.; Cai, Y.; Bian, Z.; Yang, S.; Liu, A. Oxidase mimicking nanozyme: Classification, catalytic mechanisms and sensing applications. *Coord. Chem. Rev.* **2024**, *520*, 216166. [CrossRef]
23. Xi, Z.; Xie, J.; Hu, J.; Wang, Q.-C.; Wang, Z.; Yang, X.; Zong, L.; Zhang, M.; Sun, X.; Sun, S.; et al. Polyvinylpyrrolidone-Coated Cubic Hollow Nanocages of $PdPt_3$ and $PdIr_3$ as Highly Efficient Self-Cascade Uricase/Peroxidase Mimics. *Nano Lett.* **2024**, *24*, 3432–3440. [CrossRef] [PubMed]
24. Jia, T.; Li, D.; Du, J.; Fang, X.; Gerasimov, V.; Ågren, H.; Chen, G. A bimodal type of AgPd Plasmonic Blackbody Nanozyme with boosted catalytic efficacy and synergized photothermal therapy for efficacious tumor treatment in the second biological window. *J. Nanobiotechnol.* **2022**, *20*, 424. [CrossRef] [PubMed]
25. Wang, X.; Shu, C.; Wang, G.; Han, P.; Zheng, L.; Xu, L.; Chen, Y. Recent progress of noble metal-based nanozymes: Structural engineering and biomedical applications. *Nanoscale* **2025**, *17*, 10557–10580. [CrossRef] [PubMed]
26. Fang, G.; Li, W.; Shen, X.; Perez-Aguilar, J.M.; Chong, Y.; Gao, X.; Chai, Z.; Chen, C.; Ge, C.; Zhou, R. Differential Pd-nanocrystal facets demonstrate distinct antibacterial activity against Gram-positive and Gram-negative bacteria. *Nat. Commun.* **2018**, *9*, 129. [CrossRef] [PubMed]
27. Chong, Y.; Dai, X.; Fang, G.; Wu, R.; Zhao, L.; Ma, X.; Tian, X.; Lee, S.; Zhang, C.; Chen, C.; et al. Palladium concave nanocrystals with high-index facets accelerate ascorbate oxidation in cancer treatment. *Nat. Commun.* **2018**, *9*, 4861. [CrossRef] [PubMed]
28. Cao, S.; Long, Y.; Xiao, S.; Deng, Y.; Ma, L.; Adeli, M.; Qiu, L.; Cheng, C.; Zhao, C. Reactive oxygen nanobiocatalysts: Activity-mechanism disclosures, catalytic center evolutions, and changing states. *Chem. Soc. Rev.* **2023**, *52*, 6838–6881. [CrossRef] [PubMed]
29. Sheng, J.; Wu, Y.; Ding, H.; Feng, K.; Shen, Y.; Zhang, Y.; Gu, N. Multienzyme-Like Nanozymes: Regulation, Rational Design, and Application. *Adv. Mater.* **2023**, *36*, e2211210. [CrossRef] [PubMed]
30. Karagas, M.R.; Gossai, A.; Pierce, B.; Ahsan, H. Drinking Water Arsenic Contamination, Skin Lesions, and Malignancies: A Systematic Review of the Global Evidence. *Curr. Environ. Health Rep.* **2015**, *2*, 52–68. [CrossRef] [PubMed]
31. Shah, A.; Arjunan, A.; Baroutaji, A.; Zakharova, J. A review of physicochemical and biological contaminants in drinking water and their impacts on human health. *Water Sci. Eng.* **2023**, *16*, 333–344. [CrossRef]

32. Shannon, M.A.; Bohn, P.W.; Elimelech, M.; Georgiadis, J.G.; Mariñas, B.J.; Mayes, A.M. Science and technology for water purification in the coming decades. *Nature* **2008**, *452*, 301–310. [CrossRef] [PubMed]
33. Diao, Q.; Chen, X.; Tang, Z.; Li, S.; Tian, Q.; Bu, Z.; Liu, H.; Liu, J.; Niu, X. Nanozymes: Powerful catalytic materials for environmental pollutant detection and degradation. *Environ. Sci. Nano* **2024**, *11*, 766–796. [CrossRef]
34. Wong, E.L.S.; Vuong, K.Q.; Chow, E. Nanozymes for Environmental Pollutant Monitoring and Remediation. *Sensors* **2021**, *21*, 408. [CrossRef] [PubMed]
35. Qu, X.; Alvarez, P.J.; Li, Q. Applications of nanotechnology in water and wastewater treatment. *Water Res.* **2013**, *47*, 3931–3946. [CrossRef] [PubMed]
36. Asati, A.; Santra, S.; Kaittanis, C.; Nath, S.; Perez, J.M. Oxidase-Like Activity of Polymer-Coated Cerium Oxide Nanoparticles. *Angew. Chem.* **2009**, *121*, 2344–2348. [CrossRef]
37. Nayak, S.; Hansdah, S.; Palai, S.P.; Malik, G.C.; Singh, B.; Fawcett, D.; Poinern, G.E.J.; Parhi, P.K. Nanozyme-based remediation of complex wastewater streams: A focus on emerging contaminants. *Inorg. Chem. Commun.* **2026**, *186*, 116268. [CrossRef]
38. Pera-Titus, M.; García-Molina, V.; Baños, M.A.; Giménez, J.; Esplugas, S. Degradation of chlorophenols by means of advanced oxidation processes: A general review. *Appl. Catal. B Environ.* **2004**, *47*, 219–256. [CrossRef]
39. Elimelech, M.; Phillip, W.A. The Future of Seawater Desalination: Energy, Technology, and the Environment. *Science* **2011**, *333*, 712–717. [CrossRef] [PubMed]
40. Pereira, M.C.; Oliveira, L.C.A.; Murad, E. Iron oxide catalysts: Fenton and Fentonlike reactions—A review. *Clay Miner.* **2012**, *47*, 285–302. [CrossRef]
41. Cheng, N.; Li, J.; Liu, D.; Lin, Y.; Du, D. Single-Atom Nanozyme Based on Nanoengineered Fe–N–C Catalyst with Superior Peroxidase-Like Activity for Ultrasensitive Bioassays. *Small* **2019**, *15*, 1901485. [CrossRef]
42. Liu, J.; Hu, X.; Hou, S.; Wen, T.; Liu, W.; Zhu, X.; Yin, J.-J.; Wu, X. Au@Pt core/shell nanorods with peroxidase- and ascorbate oxidase-like activities for improved detection of glucose. *Sens. Actuators B Chem.* **2012**, *166–167*, 708–714. [CrossRef]
43. Guo, L.; Zhao, A.; Liu, G.; Ma, L.; He, Y.; Zheng, X.; Liu, Y.; Zhou, L.; Jiang, Y.; Gao, J. Zr-MOF-Based Enzyme Mimic Catalytic Membrane for Removal of Organophosphorus Pesticides. *ACS Appl. Nano Mater.* **2024**, *7*, 26344–26355. [CrossRef]
44. Yi, G.; Tao, Z.; Fan, W.; Zhou, H.; Zhuang, Q.; Wang, Y. Copper Ion-Induced Self-Assembled Aerogels of Carbon Dots as Peroxidase-Mimicking Nanozymes for Colorimetric Biosensing of Organophosphorus Pesticide. *ACS Sustain. Chem. Eng.* **2024**, *12*, 1378–1387. [CrossRef]
45. Liu, N.; Liang, G.; Dong, X.; Qi, X.; Kim, J.; Piao, Y. Stabilized magnetic enzyme aggregates on graphene oxide for high performance phenol and bisphenol A removal. *Chem. Eng. J.* **2016**, *306*, 1026–1034. [CrossRef]
46. Essam, T.; Amin, M.A.; El Tayeb, O.; Mattiasson, B.; Guieysse, B. Solar-based detoxification of phenol and p-nitrophenol by sequential TiO2 photocatalysis and photosynthetically aerated biological treatment. *Water Res.* **2007**, *41*, 1697–1704. [CrossRef] [PubMed]
47. Natalio, F.; André, R.; Hartog, A.F.; Stoll, B.; Jochum, K.P.; Wever, R.; Tremel, W. Vanadium pentoxide nanoparticles mimic vanadium haloperoxidases and thwart biofilm formation. *Nat. Nanotechnol.* **2012**, *7*, 530–535. [CrossRef] [PubMed]
48. Guliy, O.I.; Bunin, V.D. Optical Sensor Systems for Antibiotic Detection in Water Solutions. *Water* **2026**, *18*, 125. [CrossRef]
49. Patel, S.; Jamunkar, R.; Sinha, D.; Monisha; Patle, T.K.; Kant, T.; Dewangan, K.; Shrivas, K. Recent development in nanomaterials fabricated paper-based colorimetric and fluorescent sensors: A review. *Trends Environ. Anal. Chem.* **2021**, *31*, e00136. [CrossRef]
50. Sun, J.; Yan, M.; Tao, G.; Su, R.; Xiao, X.; Wu, Q.; Chen, F.; Wu, X.-L.; Lin, H. A single-atom manganese nanozyme mediated membrane reactor for water decontamination. *Water Res.* **2024**, *268*, 122627. [CrossRef] [PubMed]
51. Feng, Y.; Liu, Z.; Zhang, K.; Deng, F.; Ning, C. Selenium-doped NiCo2O4 drives nanozyme innovation: New ideas in water disinfection. *J. Clean. Prod.* **2025**, *518*, 145875. [CrossRef]
52. Kim, N.; Collins, D.S.; Donghia, N.M.; Miller, B.S.; Sallum, H.M.; Lybbert, S.R.; Perini, E.; Niemi, J.B.; Collins, J.J.; Nguyen, P.Q. A field-deployable CRISPR-based biosensing platform for monitoring marine ecosystems. *Nat. Sustain.* **2026**, *9*, 51–64. [CrossRef]
53. Bhatnagar, A.; Hogland, W.; Marques, M.; Sillanpää, M. An overview of the modification methods of activated carbon for its water treatment applications. *Chem. Eng. J.* **2013**, *219*, 499–511. [CrossRef]
54. Ali, H.S.H.M.; Sumiya; Anwar, Y.; Al-Ghamdi, Y.O.; Fakieh, M.; Khan, S.A. Revealing the Effect of MnO_2, Activated Carbon and MnO_2/Activated Carbon on Chitosan Polymer Host Fabricated Co NPs: Antibacterial Performance and Degradation of Organic Compounds. *Polymers* **2022**, *14*, 627. [CrossRef] [PubMed]
55. Fu, H.; Li, H.; He, Q.; Du, G.; Li, J.; Zhang, Y.; Liang, Y.; Lin, B. Flexible fiber composite functional materials based on Fe-MOFs nanozyme catalytic activity for efficient point-of-use water disinfection. *Chem. Eng. J.* **2024**, *490*, 151879. [CrossRef]
56. Thao, N.T.T.; Nguyen, D.H.; Kien, P.T.; Duong, T.-T.; Lien, N.T.K.; Tri, D.Q.; Linh, D.T.T.; Lan, N.T. Effect of Magnetic Magnetite (Fe_3O_4) Nanoparticle Size on Arsenic (V) Removal from Water. *J. Nanosci. Nanotechnol.* **2021**, *21*, 2576–2581. [CrossRef] [PubMed]
57. Qudsieh, I.Y.; Ali, M.A.; Maafa, I.M. Effect of water matrix on photocatalytic degradation of organic pollutants in water: A literature review. *Rev. Chem. Eng.* **2025**, *41*, 539–573. [CrossRef]

58. Yang, X.; Rosario-Ortiz, F.L.; Lei, Y.; Pan, Y.; Lei, X.; Westerhoff, P. Multiple Roles of Dissolved Organic Matter in Advanced Oxidation Processes. *Environ. Sci. Technol.* **2022**, *56*, 11111–11131. [CrossRef] [PubMed]
59. Yan, Y.; Wei, Z.; Duan, X.; Long, M.; Spinney, R.; Dionysiou, D.D.; Xiao, R.; Alvarez, P.J.J. Merits and Limitations of Radical vs. Nonradical Pathways in Persulfate-Based Advanced Oxidation Processes. *Environ. Sci. Technol.* **2023**, *57*, 12153–12179. [CrossRef] [PubMed]
60. Nidheesh, P.V.; Kaur, K.; Anukrishna, R.G.; Prathish, K.P. From scavenger to catalyst: The emerging role of chloride in peroxymonosulfate-based advanced oxidation processes. *Environ. Sci. Water Res. Technol.* **2025**, *11*, 2480–2498. [CrossRef]
61. Niu, X.; Shi, Q.; Zhu, W.; Liu, D.; Tian, H.; Fu, S.; Cheng, N.; Li, S.; Smith, J.N.; Du, D.; et al. Unprecedented peroxidase-mimicking activity of single-atom nanozyme with atomically dispersed Fe–Nx moieties hosted by MOF derived porous carbon. *Biosens. Bioelectron.* **2019**, *142*, 111495. [CrossRef] [PubMed]
62. Gadgil, A. Drinking water in developing countries. *Annu. Rev. Energy Environ.* **1998**, *23*, 253–286. [CrossRef]
63. Nel, A.; Xia, T.; MädLer, L.; Li, N. Toxic Potential of Materials at the Nanolevel. *Science* **2006**, *311*, 622–627. [CrossRef] [PubMed]
64. Tangaa, S.R.; Selck, H.; Winther-Nielsen, M.; Khan, F.R. Trophic transfer of metal-based nanoparticles in aquatic environments: A review and recommendations for future research focus. *Environ. Sci. Nano* **2016**, *3*, 966–981. [CrossRef]
65. Zhao, X.; Yu, M.; Xu, D.; Liu, A.; Hou, X.; Hao, F.; Long, Y.; Zhou, Q.; Jiang, G. Distribution, Bioaccumulation, Trophic Transfer, and Influences of CeO_2 Nanoparticles in a Constructed Aquatic Food Web. *Environ. Sci. Technol.* **2017**, *51*, 5205–5214. [CrossRef] [PubMed]
66. Nizam, N.U.M.; Hanafiah, M.M.; Woon, K.S. A Content Review of Life Cycle Assessment of Nanomaterials: Current Practices, Challenges, and Future Prospects. *Nanomaterials* **2021**, *11*, 3324. [CrossRef] [PubMed]
67. Kumar, A.S.K.; Tseng, W.-B.; Arputharaj, E.; Huang, P.-J.; Tseng, W.-L.; Bajda, T. Covalent Organic Framework Nanosheets as an Enhancer for Light-Responsive Oxidase-like Nanozymes: Multifunctional Applications in Colorimetric Sensing, Antibiotic Degradation, and Antibacterial Agents. *ACS Sustain. Chem. Eng.* **2023**, *11*, 6956–6969. [CrossRef]
68. Kumari, A.; Kamaraj, N.; Selvaraj, R.; Nanoth, R. Emerging trends and future outlook on chromium removal in the lab, pilot scale, and industrial wastewater system: An updated review exploring 10 years of research. *Environ. Monit. Assess.* **2025**, *197*, 547. [CrossRef] [PubMed]
69. Martínez-Zamudio, L.Y.; González-González, R.B.; Araújo, R.G.; Hernández, J.A.R.; Flores-Contreras, E.A.; Melchor-Martínez, E.M.; Parra-Saldívar, R.; Iqbal, H.M. Emerging pollutants removal from leachates and water bodies by nanozyme-based approaches. *Curr. Opin. Environ. Sci. Health* **2023**, *37*, 100522. [CrossRef]
70. Hamed, E.M.; Li, S.F.Y. Bridging the Gap Between Nanozyme Innovation and Real-World Environmental Solutions. *Anal. Chem.* **2026**, *98*, 15277–15286. [CrossRef] [PubMed]
71. Saini, N.; Choudary, R.; Chopra, D.S.; Singh, D.; Singh, N. Nanozymes: Classification, synthesis and challenges. *Appl. Nanosci.* **2023**, *13*, 6433–6443. [CrossRef]
72. Meng, Y.; Li, W.; Pan, X.; Gadd, G.M. Applications of nanozymes in the environment. *Environ. Sci. Nano* **2020**, *7*, 1305–1318. [CrossRef]
73. Liu, Q.; Zhang, A.; Wang, R.; Zhang, Q.; Cui, D. A Review on Metal- and Metal Oxide-Based Nanozymes: Properties, Mechanisms, and Applications. *Nano-Micro Lett.* **2021**, *13*, 154. [CrossRef] [PubMed]
74. Yu, Y.; Zhang, M.; Fan, K. Artificial intelligence-driven revolution in nanozyme design: From serendipity to rational engineering. *Mater. Horiz.* **2025**, *12*, 7779–7813. [CrossRef] [PubMed]
75. Parkinson, J.; Tayler, K. Decentralized wastewater management in peri-urban areas in low-income countries. *Environ. Urban.* **2003**, *15*, 75–90. [CrossRef]
76. Adams, E.A.; Zulu, L.; Ouellette-Kray, Q. Community water governance for urban water security in the Global South: Status, lessons, and prospects. *WIREs Water* **2020**, *7*, e1466. [CrossRef]
77. Tanzanian Scientist Proposes Nano Innovations to Address Health Problems. Available online: https://www.who.int/news-room/feature-stories/detail/tanzanian-scientist-proposes-nano-innovations-to-address-health-problems (accessed on 6 February 2026).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.