Journal of
Materials Chemistry A

Materials for energy and sustainability

Accepted Manuscript

This article can be cited before page numbers have been issued, to do this please use: R. Umapathi, H. Kim, D. Kim, A. Gaur, V. Chaudhary, M. Safarkhani, S. Shin, T. J. Park, G. Mohana Rani , K. Shin and Y. S. Huh, *J. Mater. Chem. A*, 2026, DOI: 10.1039/D5TA09692H.

This is an Accepted Manuscript, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this Accepted Manuscript with the edited and formatted Advance Article as soon as it is available.

You can find more information about Accepted Manuscripts in the Information for Authors.

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal's standard Terms & Conditions and the Ethical guidelines still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this Accepted Manuscript or any consequences arising from the use of any information it contains.

ROYAL SOCIETY OF CHEMISTRY

rsc.li/materials-a

View Article Online
DOI: 10.1039/D5TA09692H

Innovative Nanozymes: Emerging Platforms for Efficient Pesticide Detection

Reddicherla Umapathi[1,a], Hanseung Kim[1,a], Donghyeon Kim[1], Ashish Gaur,[2] Vishal Chaudhary,[3] Moein Safarkhani[4], Sujeong Shin[5], Tae Jung Park[6], Gokana Mohana Rani[4,], Kwangsoo Shin[7,*], Yun Suk Huh[1,*]*

[1]*NanoBio High-Tech Materials Research Center, Department of Biological Sciences and Bioengineering, Inha University, Incheon 22212, Republic of Korea*

[2]*Department of Energy Science, Sungkyunkwan University, Suwon, 16419 Republic of Korea*

[3]*Centre for Theoretical Physics and Natural Philosophy, Nakhonsawan Studiorum for Advanced Studies, Mahidol University, Nakhonsawan 60130, Thailand*

[4]*Department of Energy and Materials Engineering, Dongguk University-Seoul, Seoul, 04620, Republic of Korea*

[5]*New Hazardous Substances Team, Department of Food Safety Evaluation, National Institute of Food and Drug Safety Evaluation, Ministry of Food and Drug Safety, Cheongju-si 28159, Korea*

[6]*Department of Chemistry, Research Institute of Chem-Bio Diagnostic Technology, Chung-Ang University, 84 Heukseok-ro, Dongiak-gu, Seoul 06974, Republic of Korea*

[7]*Department of Polymer Science and Engineering and Program in Environmental and Polymer Engineering, Inha University, Incheon 22212, Republic of Korea*

***Corresponding authors**:

Prof. Yun Suk Huh (yunsuk.huh@inha.ac.kr)

Prof. Kwangsoo Shin (kwangsoo.shin@inha.ac.kr)

Dr. Gokana Mohana Rani (gmohanarani@gmail.com)

[a]Equally contributed authors (RU and HK)

View Article Online
DOI: 10.1039/D5TA09692H

Abstract

Effective and timely detection of pesticide residues is highly crucial as these toxic chemical residues cause several effects on humans and environment. Increasing necessity towards progression of detection systems has flashed considerable curiosity in analytical sensing technologies. Substantial research advancements have been made in analytical chemistry, nanozymes, and materials chemistry, for detection of pesticides. A relatively innovative sensing strategy that has gained widespread attention is based on natural enzyme mimicking catalytic property of nanomaterials, commonly referred to as nanozyme activity. Nanozymes properties make them highly promising sensing materials for precisely determining the pesticides with low detection limits, wide linear ranges, excellent selectivity, and appreciable sensitivity. Apart from increasing the sensing behaviors, these characteristics will facilitate in designing versatile sensing platforms that integrate surface enhanced Raman scattering (SERS), colorimetric, electrochemical, and fluorescence transduction procedures. In this review, we provided a critical overview on nanozymes for pesticides detection, encompassing their material compositions, strategies for activity enhancement, output signals, and methodologies. Explicitly discussed the advances made in nanozyme-based colorimetric, electrochemical, SERS, and fluorescence sensing strategies for the substantial quantification of pesticides. Outlined the strategic advantages and detailed mechanisms for the detection of pesticides. Highlighted the working principle and salient features of various nanozyme-based sensors, to enhance the sensing efficiency. Finally, challenges and associated limitations were discussed to realize full potential of nanozyme-based optical and electrochemical sensors.

Keywords: Nanozymes, Pesticides, Colorimetric Sensors, Fluorescence Sensors, Electrochemical Sensors, SERS Sensors, Emerging Contaminants.

View Article Online
DOI: 10.1039/D5TA09692H

1. Introduction

Pesticides denote a broad category of chemical substances utilized chiefly for the management of weeds, pathogens, pests, and diseases in livestock production, and forestry. Pesticides can be classified as rodenticides, acaricides, insecticides, plant growth regulators, fungicides, and herbicides depending on their desired application. Over the past few years, ongoing population expansion and rising demand for food products have rendered the importance of pesticides in aquaculture, animal husbandry, agriculture, and the protection of industrial items from pests and molds. All these instances lead to an increase in the consumption of pesticides.[1-4] The essential application of pesticides for improving agricultural output has become unavoidable. The excessive consumption, improper utilization, and abuse of pesticides, along with their exponential expansion in use, has led to significant pesticide residues that threaten human well-being and ecosystems. Unfortunately, the indiscriminate and unregulated use of these pesticides transcends the designated target areas, with pesticide residues persisting for months or even years. Pesticides released into the surrounding atmosphere permeate soil and aquatic ecosystems through air circulation, where they are frequently absorbed and accumulated by the root systems and medicinal plants, ultimately accumulating in the bodies of humans through the food chain.[5-10] The lack of precise information has incited extensive insect infestations, presenting considerable health hazards to people and other organisms because of residual pesticides in food. The existence of even minimal quantities of these residual pesticides has become a significant obstacle to international trading in the food commodities. Prolonged exposure of pesticides will result in reproductive toxicity, immunotoxicity, neurotoxicity, hepatotoxicity, and severe epithelial toxicity, moreover, in extreme cases it will lead to the development of cardiovascular diseases, cancer, fetal malformations, and atherosclerosis. Younger populations will be more prone to

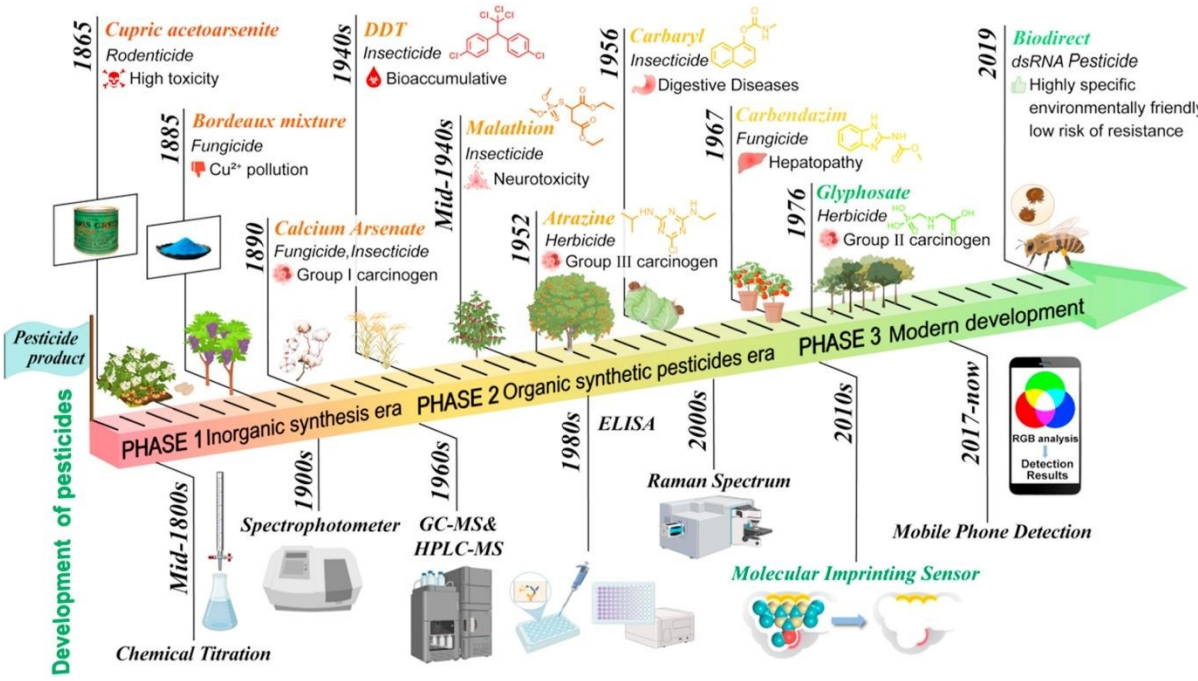
View Article Online
DOI: 10.1039/D5TA09692H

these toxic consequences. As a result, pesticide residues have emerged as a major potential hazard to human health. In response to this issue, many nations and globally recognized organizations have set maximum residue limits for pesticides across different matrices and have enacted prompt restrictions and bans on high-risk pesticides, progressively substituting them with low-toxicity synthetic substitutes. Modern medicine encounters intrinsic constraints in therapy due to the emergence of novel diseases caused by the pesticides. Hence, it is imperative to limit the usage and spraying of pesticides to the plants and to timely quantify the pesticides in the surrounding environment.[11-15]

Conventional pesticide quantification techniques such as mass spectrometry (MS), high-performance liquid chromatography (HPLC), gas chromatography (GC), and their combined methods HPLC-MS, and GC-MS requires pumps with high pressures to enable interactions between the analytes and functional components of the mobile and stationary phases, permitting the quantification of target compounds based on the peak area. Moreover, mass spectrometry is utilized to ionize sample molecules, facilitating qualitative investigation of the molecular structures. Despite achieving exceptional sensitivity and accuracy, these systems are constrained by inherent restrictions, such as the need for skilled operators, complex and costly apparatus, intricate pretreatment processes, the requirement for trained staff, and the logistical challenges of on-site detection. Recent literature from the past ten years indicates that the swift advancement of sophisticated sensing systems has emerged as one of the most effective solutions to the issues and challenges posed by conventional pesticide quantification techniques.[5-10, 14, 15] Currently, intensified demand for straightforward, rapid, sensitive, and selective detection platforms has been noticed. Among these technologies, sensors exhibiting

View Article Online
DOI: 10.1039/D5TA09692H

excellent sensitivity and thigh selectivity have been identified as viable platforms for pesticide residue analysis, owing to their capacity for user-friendly high-throughput, low-cost, and on-site detection.[5-10, 14, 15]



Scheme 1 The development history of pesticides and their related detection method. Reproduced from reference[4] with permission from Elsevier, copyright 2025.

For the quantification of the residual pesticides, different types of sensors have been employed depending on their conversion mechanism including, electrochemical, optical, acoustic, and thermal sensors, etc**.** Among these, electrochemical and optical sensors play a prominent role in detecting contaminants.[1-11, 14-18] Optical sensors are engineered to respond to variations in light signals resulting from the interaction between bio-recognition elements and analytes. Compared to conventional pesticide quantification techniques, optical and electrochemical sensing methodologies provides a cost effective, fast, and facile approach for

View Article Online
DOI: 10.1039/D5TA09692H

the sensitive quantification of the pesticides based on surface-enhanced Raman scattering (SERS), colorimetric, and fluorescence signal variations. Electrochemical (bio)sensors demonstrate high cost-effectiveness due to their simplistic operation, affordability, and efficient in situ detection potential, which makes them particularly valuable for real-time monitoring of pesticide residues. Scheme 1 delineates pesticides developmental trajectory and the advancement of the related sensing technologies.[4]

Sensors are distinguished by their portability, affordability, and minimal utilization of samples and reagents. A variety of sensors have been designed for the identification of residual pesticides in highly complex matrix systems. Nevertheless, the extensive utilization of the traditional sensors in complex samples has been substantially restricted owing to the intrinsic limitations of recognition elements, including low specificity and inadequate physicochemical stability. For example, sensors based on urease, peroxidase, and acetylcholinesterase (AChE), are prone to the inactivation, this can be due to the deformations in structures caused by reactive oxygen species, pH fluctuations, and elevated temperatures produced during reactions in aquatic or soil environments. Similarly, DNA sensors, microbial sensors, and immunosensors are highly prone to environmental factors, resulting in the degradation of probe. Sensing platforms demonstrate a degree of stability in complicated environments, nevertheless, their ability to select certain pesticides is limited. To address these challenges, nanozymes have been utilized as potential sensing platforms owing to their sensitivity, prospective stability, ease of preparation, surface tunability, and compatibility with the target analytes.[2, 3, 19-22]

View Article Online
DOI: 10.1039/D5TA09692H

Unlike enzymes and natural enzymes, nanozymes offer significant potential for practical applications by reducing the overall costs and by enhancing the sensing performance. To date, substantial research efforts has been made in designing various types of nanozymes for the detection of pesticides. The nanozyme nanomaterials with enzyme-mimicking catalytic properties have demonstrated substantial potential with excellent stability under harsh conditions, intrinsic catalytic activity, tunable surface chemistry, and structural diversity. These properties make them highly promising sensing materials for precisely determining the pesticides with low detection limits, wide linear ranges, excellent selectivity, and appreciable sensitivity.[2, 3, 19-22] Apart from increasing the sensing behaviors, these characteristics will facilitate in designing versatile sensing platforms that integrate SERS, colorimetric, electrochemical, and fluorescence transduction procedures. These systems have substantial advantages including rapid response, portability, low cost, and capability for on-site detection, which are crucial for environmental protection and ensuring food security and food safety. Although recent progress in nanozymes have facilitated excellent pesticide recognition, there remains a lack of comprehensive reviews, predominantly discussing strategic advantages and design principles of nanozyme-based colorimetric, electrochemical, SERS, and fluorescence platforms. This study aims to summarize the advances made in pesticide detection through various transduction approaches, considering significant breakthroughs in advanced methods and existing lack of thorough evaluations. The review particularly emphasizes major pesticide families, including organophosphorus, neonicotinoids, carbamates, fungicides, and herbicides, which are used widely in agriculture and are among the most often detected pesticide residues in food and environmental samples, thereby providing a comprehensive assessment of current detection approaches. Comprehensively investigated nanozymes based colorimetric, fluorescence, SERS, and electrochemical sensors for pesticide detection. Strategic advantages

View Article Online
DOI: 10.1039/D5TA09692H

of nanozyme-based detection methods have been explicitly elucidated. Outlined the detailed mechanisms for detection of pesticides. Thoroughly discussed the current limitations and key challenges of each sensing modality and suggested future research trends and perspectives that may accelerate the fabrication of advanced nanozyme-based pesticide sensors. This review aims to offer a holistic overview and comprehensive understanding of state-of-the-art nanozyme-based sensors and directed future initiatives for the systematic fabrication of next generation smart sensing strategies for the on-site pesticide monitoring. The relevant literature was searched systematically using the major scientific databases including "Web of Science", "Scopus", and "Google Scholar". The search was carried out using combinations of keywords such as "nanozymes," "pesticides," "colorimetric sensors," "fluorescence sensors," "electrochemical sensors," and "SERS sensors."

2. An overview of nanozymes

Enzymes are a category of biological macromolecular catalysts that are crucial for both the industrial and biological transformation procedures. Natural enzymes have consistently influenced biosensor technologies owing to their exceptional target selectivity. Nonetheless, the extensive utilization of naturally occurring enzymes have been restricted, particularly in challenging environments, owing to their inherent limitations, such as susceptibility to external factors, low operational stability, elevated costs, limited lifespans, specific requirements for storage, reduced stability under atmospheric conditions, and difficult yet costly production and extraction procedures.[23, 24] Hence, substantial research attempts have been performed to address these limitations. This has resulted in the design and development of several noteworthy enzyme-mimicking platforms. Among these, particularly nanozymes have

View Article Online
DOI: 10.1039/D5TA09692H

received a great deal of interest during the last decade. Substantial progress in nanoscience, protein engineering, and nanozyme engineering has broadened the scope and strategies to address the challenges associated with the natural enzymes.[25, 26] The identification of oxidoreductase-like and hydrolase-like nanozymes is a notable advancement in nanobiotechnology. Nanozymes, or artificial enzymes, can surpass natural enzymes owing to their versatility, catalytic efficiency, stability in harsh environments, superior shelf-life, ease of modification, enzyme-mimicking capabilities, high stability, cost-effectiveness, biocompatibility, distinctive surface chemistry, tunable surfaces, and robustness. These characteristics allowed them to use in wide array of nanotechnology applications, including food safety, biosensors, environmental protection, antioxidant agents, disease diagnosis, drug delivery, antibacterial agents, imaging and treatment, and tissue engineering. Moreover, nanozymes are potentially using in environmental sciences, chemical engineering, bio-medical field, industrial settings, agricultural sectors, and food safety.[20-22] Nanozymes are often categorized as nanomaterials exhibiting enzyme-mimicking activity as catalysts. So far, several nanomaterials have been synthesized, comprising but not limited to noble metal nanoparticles, carbon-based nanomaterials, metal oxides, polymetallic nanostructures, and metal-organic frameworks (MOFs), have been studied for enzyme-mimicking activities.[27, 28] The unique physicochemical characteristics of nanomaterials, which can be customized to fulfill particular application needs, are intricately associated with their enzyme like activities. Enzymatic activity characteristics like substrate multienzyme-like behavior catalytic efficiency, and selectivity, are dependent upon the physicochemical features of nanomaterials, which encompass shape, self-assembly, size, surface modification, and crystallographic state.[29, 30] Furthermore, temperature and pH are critical parameters that can significantly influence the catalytic function of nanozymes. Nanozymes, as novel materials, have exhibited significant

View Article Online
DOI: 10.1039/D5TA09692H

potential in the field of electroanalytical chemistry for the detection of potential environmental contaminants.[20-22]

In addition to electroanalytical performance, the fabrication of nanozyme-based pesticide sensors should be aligned with the sustainability and green chemistry principles. Nanozymes synthesized through green chemistry principles represent a transformative perspective integrating sustainability with the advanced electrocatalytic and nano-catalytic functionalities.[31] Recent investigations substantially emphasize low-energy and environmentally benign synthesis routes to avoid the usage of toxic reagents and to reduce energy consumption. Appropriate selection of materials also plays an essential role in sustainability. Noble metal-based nanozymes (e.g., gold, platinum, palladium) exhibit exceptional catalytic activity, yet their high cost and limited availability raise concerns regarding material criticality and large-scale deployment.[32] On the other hand, nanozymes based on earth-abundant materials, including transition metal oxides, carbon-based nanostructures, and metal organic framework (MOF)-derived systems, provide more cost-effective and sustainable alternatives. From the application point of view, the fabrication of disposable or reusable sensing platforms must consider lifecycle and environmental impact. Nanozymes immobilization on the solid support facilitates reusability and reduces material waste, whereas the flexible or paper-based substrates offer biodegradable, disposable, and low-cost sensing frameworks suitable for the field applications.[33] Moreover, the advancement of field-deployable sensing technologies, including portable electrochemical devices, smartphone-integrated colorimetric assays, and on-site SERS sensing platforms, facilitates low-resource detection in agricultural and ecological environments without requiring complex instrumentation.[22] Despite these advancements, comprehensive lifecycle assessments and

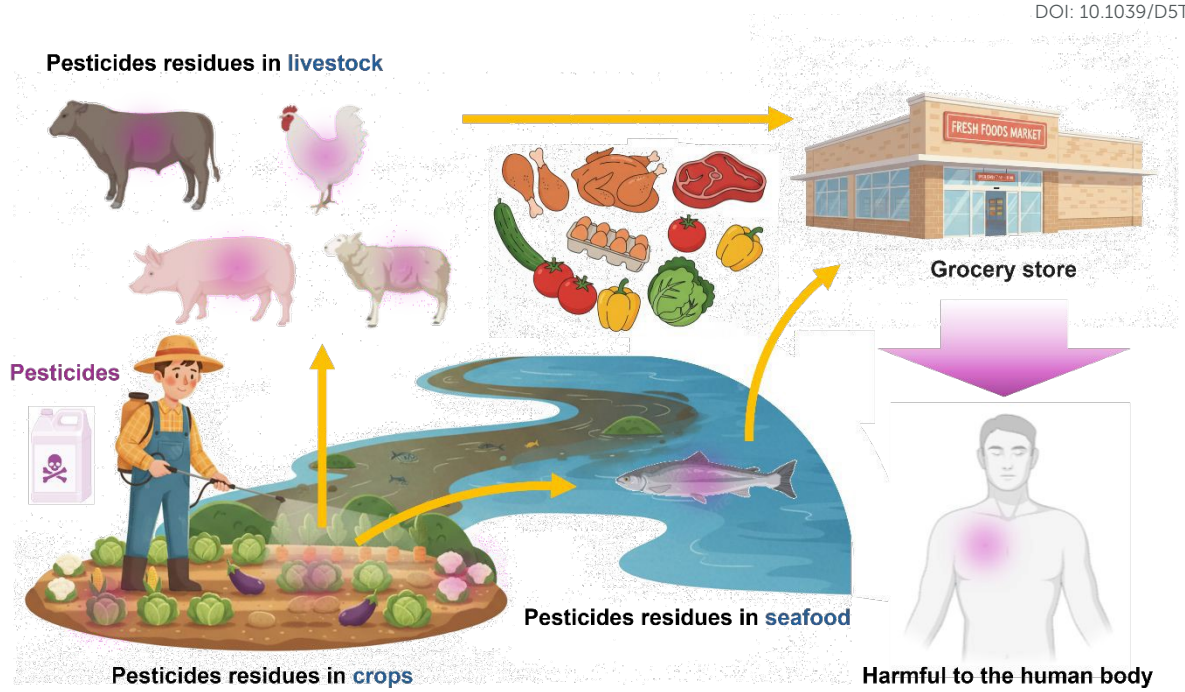
View Article Online
DOI: 10.1039/D5TA09692H

environmental impact analyses of nanozyme materials remain limited. Future research should focus on selection of sustainable materials, scalable fabrication methods, and green synthesis strategies, while also considering environmental safety, recyclability, and real-world applicability to ensure that nanozyme-based pesticide sensing technologies contribute to sustainable monitoring practices.[34, 35]

3. Toxic impact of pesticides on human and environmental health

Pesticide residues are toxic chemicals that are often found in vegetables, fruits, cattle feed, and agricultural food products, which occur in the form of metabolites, transformation products, impurities, and reaction products. The effective and strategic use of pesticides requires proper leaf coverage. However, farmers tend to apply excessive amounts of pesticides to ensure that all crops are thoroughly covered.[1, 4, 11, 12, 36] Therefore, the dietary intake of pesticide-contaminated fruits, vegetables, edible plant leaves, and other food crops is currently among the greatest threats to human health worldwide, and food poisoning incidents caused by the accidental ingestion of chemical pesticide residues are not uncommon. Even low concentrations of pesticide residues may affect not only food and water safety but may also disrupt ecosystem dynamics. Chemical pesticide residues may affect human health through direct exposure or indirect exposure via the consumption of contaminated food or water.[6-12] Scheme 2 shows the routes of food contamination by pesticides.

View Article Online
DOI: 10.1039/D5TA09692H



Scheme 2. Systemic pathways of pesticide residues from environmental application to human intake.

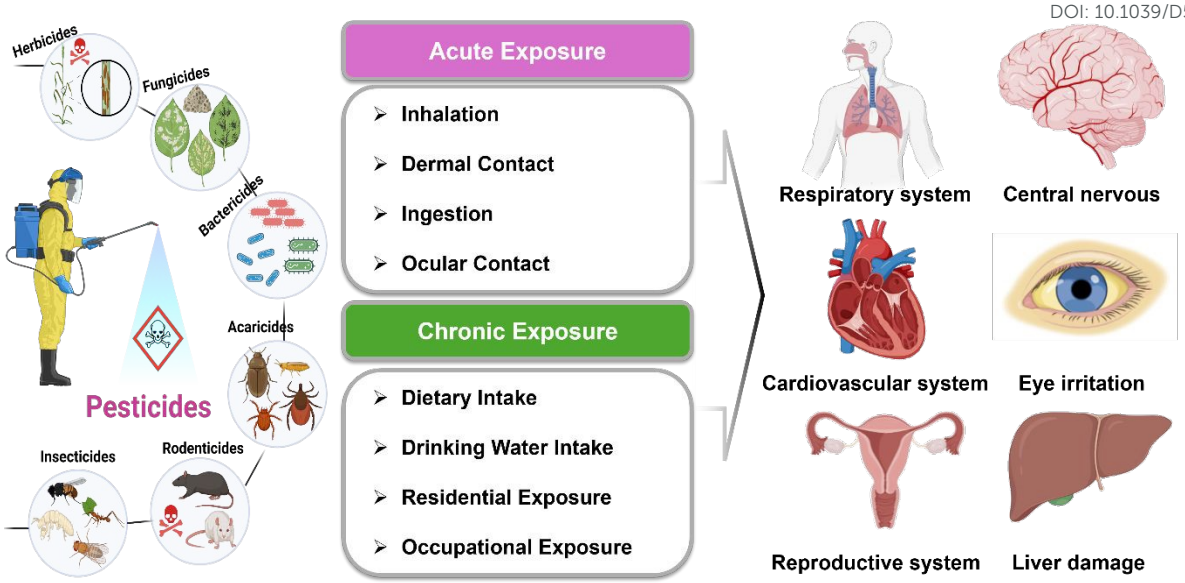
The key routes of pesticide exposure are ingestion, inhalation, and dermal penetration. Chronic diseases have been reported in individuals that were exposed to pesticides. Direct or indirect exposure to pesticide residues may cause nausea, headaches, skin irritation, birth defects, developmental toxicity, dizziness, burning eyes, cancer, reproductive disorders, chronic nephropathies, neurotoxicity, Parkinson's disease, central nervous system damage, diabetes, genetic damage, amyotrophic lateral sclerosis, cardiovascular diseases, vomiting, respiratory and digestive disturbances, and death. Organophosphorus pesticides (OPs) are known to affect the reproductive system, particularly in males. For instance, parathion exposure led to testicular abnormalities in male mice, in addition to chromosomal aberrations in the peripheral lymphocytes of mice. Although pesticides are crucial for pest management and plant

View Article Online
DOI: 10.1039/D5TA09692H

growth and productivity, the detection and regulation of pesticide residues in agricultural food products and commodities should be strictly monitored and regulated.[6-12, 19]

The use of chemical pesticides has considerably increased crop yields; however, their utilization poses serious environmental risks. Pesticide residues have been recently identified in a wide variety of environmental samples due to the rapid expansion of anthropogenic activities. Massive amounts of chemical pesticides and other contaminants have also been released into the atmosphere due to the recent industrialization of the agriculture sector.[37-39] Additionally, pesticides are easily volatilized and transported, after which they are readily assimilated into ecosystems and biota. The effects of elevated pesticide concentrations in the environment may also be exacerbated by certain climate conditions, including temperature and relative humidity. Pesticides may also percolate or leach into the soil, which in turn erodes the soil and reduces its fertility and biodiversity. Further, these effects may also alter the physical characteristics of water bodies, which ultimately reduces drinking water quality.[40] Honeybees are generally considered outstanding sentinels for the evaluation of environmental pesticide pollution. Chemical pesticides have been linked to increased honeybee mortalities, hive abandonment, and decreased pollinating efficiency. In addition to honeybees, pesticide residues affect a large variety of other non-target organisms such as birds and aquatic animals.[1, 4, 11, 12, 19] Scheme 3 illustrates the adverse effects of pesticides on humans along with several disorders.

View Article Online
DOI: 10.1039/D5TA09692H



Scheme 3. Adverse effects of pesticides on humans along with several disorders.

Another major cause of pesticide pollution is the improper, unsafe, and illegal disposal of chemical pesticides. Several quantitative and analytical techniques have been developed for the identification of pesticide residues in environmental samples. Importantly, these quantitative and analytical techniques can be utilized to detect residual pesticides in environmental samples with high sensitivity and selectivity. Some studies have utilized silver, gold, zinc, copper, and iron nanoparticles as effective colorimetric probes for detection of pesticide residues in environmental samples. Recently, the Quick, Easy, Cheap, Effective, Rugged, and Safe (QuEChERS) detection approach has also garnered increasing attention.[41, 42] Importantly, several methods have been developed based on this approach for the detection of pesticides in environmental and food samples. An efficient approach to diminish pesticide pollution and its associated adverse effects is to use safer, more reliable, natural, and non-chemical pest control agents. Furthermore, pollution control should also be addressed through the creation of environmental policies and the implementation and regular monitoring of agro-

View Article Online
DOI: 10.1039/D5TA09692H

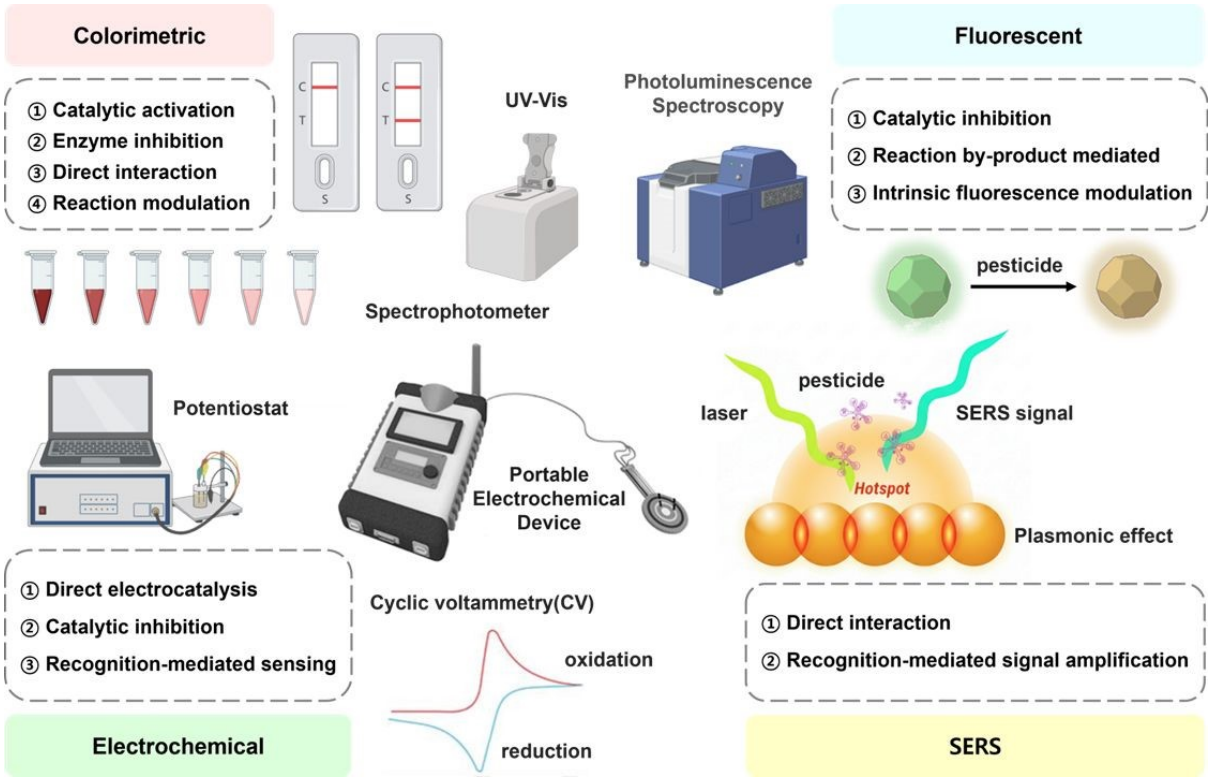
environmental indicators for pesticide risk assessment. In addition to reducing pesticide pollution risks through natural and safer practices, these strategies may be later coupled with crop rotation, land management, and field sizing to increase their efficacy.[43, 44] Furthermore, environmental, ecosystem, and biodiversity services should be clearly defined to empower stakeholders, political authorities, industry professionals, conservationists, and farmers. Therefore, global pesticide use should be strictly monitored to minimize their adverse effects on human health and environmental safety.

4. Potential of innovative nanozymes for the detection of pesticides

Nanozymes highlighted the significance of colorimetric, electrochemical, SERS, and fluorescence-based sensors for environmental monitoring applications. In this section, we conducted an in-depth exploration of the innovative potential of nanozymes for the substantial detection of pesticides. We analyzed the strategic advantages and operating principles of four key detection platforms, i.e., colorimetric, fluorescence, electrochemical, and SERS based on their signal transduction methods. In general, nanozyme-assisted pesticide detection relies on four primary mechanisms, as shown in scheme 4. (i) catalytic activity modulation where pesticides inhibit or enhance the enzyme-like activity of nanozymes; (ii) direct interaction between pesticides and nanozyme surfaces that alters catalytic or optical properties; (iii) recognition-element mediated sensing using antibodies, aptamers, or MIPs to provide selectivity; and (iv) reaction by-product mediated signal generation. These mechanisms emphasize various modes of signal transduction including colorimetric, electrochemical, fluorescence, and SERS detection systems. Interaction mechanisms between the nanozymes and pesticides were summarized and the latest research advances were elucidated. Further

View Article Online
DOI: 10.1039/D5TA09692H

demonstrated how nanozyme technology enables the development of ultra-sensitive and highly selective analytical methods. Through this multifaceted approach, we aim to provide a comprehensive outlook on the limitless potential of innovative nanozymes as next-generation, sensing technology for safeguarding future food security and environmental safety.



Scheme 4. Overview of detection mechanisms in nanozyme-based pesticide sensors.

4.1. Nanozymes for the colorimetric detection of pesticides

Pesticides are essential for enhancing agricultural productivity and play a vital role in modern agriculture. However, their residues in food and the environment are considered serious organic pollutants that pose a threat to human health and ecosystems [45]. Therefore, the

View Article Online
DOI: 10.1039/D5TA09692H

development of technologies for rapid and convenient on-site screening of these substances in agricultural fields, during distribution, or at home is a key challenge for food safety and environmental protection. While traditional analytical methods offer high accuracy and sensitivity, their on-site application is impractical due to inherent limitations such as expensive equipment, complex sample pretreatment processes such as purification or concentration, long analysis times, and the need for skilled experts [46]. One of the most promising alternatives to address these demands is the colorimetric detection method utilizing nanozymes. Colorimetric methods provide intuitive results through color changes, making them suitable for on-site use without expensive equipment or specialized training, but they have often been limited by low sensitivity and selectivity.[47] Most nanozyme-based colorimetric pesticide sensors operate through the catalytic activity modulation or through direct interaction with nanozyme surfaces, which influence the oxidation of chromogenic substrates. The advent of nanozymes has marked an innovative turning point, changing the paradigm of colorimetric detection.[23, 46] Table 1 shows the comparative analysis of nanozyme-based colorimetric sensors for pesticide detection.

Table 1. Comparative analysis of nanozyme-based colorimetric sensors for pesticide detection

Nanozyme	Pesticides	Enzyme activity	LOD	Reaction time	Recovery rates	Ref.
NH_2-CuBDC	Chlorpyrifos	Peroxidase	1.57 ng/mL	-	103.25, 103.19%	48
Fe@PCN-224 NCs	Propiconazole	Peroxidase	2.74 ng/mL	10 min	94.6-109.2%	49
GSH-Fe	Thiram	Peroxidase	0.3 μg/mL	45 min	92.4-106.9%	50
Ce/ Zr-MOF	2,2-dichlorovinyl dimethyl phosphate	Peroxidase	0.32 ng/mL	30 min	95-107%	51
ASP-Cu, BPY-Cu, GMP-Cu	Sulfonylurea pesticides	Laccase, Peroxidase	0.03 μg /mL	5 min	-	52
V_2O_5-NC	Phorate, Chlorpyrifos, Methamidophos, Methyl parathion,	Catalase, Peroxidase	7.81, 42.07, 28.23,	20 min	88.1-110.5%	53

View Article Online
DOI: 10.1039/D5TA09692H

	Glyphosate		57.91,10.14 ng/mL			
Cu-BDC-NO_2	Glyphosate	Laccase	37 ng/mL	-	90.34-96.13%	54
PtPdNPs@g-C_3N_4	Trichlorfon	Oxidase	83 pg/mL	20 min	95.78-104.34%	55
ASP-Cu	Sulfonylurea	Peroxidase	-	20 min	-	56
COF_{Fe}/CoP-Ph	Malathion	Oxidase, Catalase, Peroxidase	3.63 ng/mL	-	98.2-103.6%	57
CeO_2@NC	Carbosulfan	Oxidase	1.26 ng/mL	-	100.2-104.8%	58
ZnCo-ZIFs@MIL-101(Fe)	Glyphosate	Peroxidase	75 ng/mL	2 min	97.14-117.37%	59
Mn@NC	Phoxim	Peroxidase	1.27 ng/mL	20 min	95.00-107.93%	60
PDA/MnO_2 NPs	Carbosulfan	Oxidase	0.63 ng/mL	1 min	95.80-103.19%	61
$PtCu_{SA}$@TriMOF	Carbosulfan	Peroxidase	1.60 ng/mL	50 min	85-121%	62
Porous nitrogen−doped carbon carrier (Pt─Np─C)	Chlorpyrifos, Glyphosate, Carbaryl, Pentachloronitro benzene, Metsulfuronmethyl	Peroxidase	8.76, 4.23, 5.03, 7.38, 9.53 μg/mL	-	-	63
Zr-based metal–organic framework	Paraoxon	Phosphatase	72.65 ng/mL	-	98.1-112.5%	64
PB@Fe-COF@Au	Chlorpyrifos	Peroxidase	0.61 ng/mL	-	94/3-110.2%	65
$PtCu_3$ alloy nanocrystals	Trichlorfon	Peroxidase	0.5 ng/mL	5 min	-	66
Fe-N/C SAzyme	Malathion	Oxidase	79 pg/mL	10 min	98.6-105.4%	67
Oxidized MXene quantum dots@CuNi bimetal (MQDs@CuNi)	Glyphosate	Peroxidase	0.19 μg/mL		97.4-111.2%	68
CuO/Fe_2O_3 nanozymes	Glufosinate	Peroxidase	5.07 pg/mL	66 min	91.48-106.02%	69
Fe-N/C SAzymes	Dimethoate	Oxidase	96 pg/mL	10 min	95.01-103.94%	70
GSH-Cu	Thiram	Laccase	2.00 ng/mL	-	87.1-106.1%	71
0.5 MQDs-NiCoP/NF nanozymes	Glyphosate	Peroxidase	0.18 μg /mL	-	97.4-111.2%	72
Cu-doped carbon nanozyme	Thiophanate-methyl	Oxidase	0.04 μg /mL	-	98.1- 102.1%	73

View Article Online
DOI: 10.1039/D5TA09692H

Fe-Co MNPs	Phorate, Profenofos, Isocarbophos, Omethoate	Peroxidase	0.16, 0.16, 0.03, 1.6 ng/mL	30 min	89.19–108.35 %	[74]
N-CDs/FMOF-Zr	Glyphosate	Peroxidase	13.1, 1.5, 11.5 ng /mL	9 min	92.83–108.80%	[75]
FeCoCu flower-like structure (FeCoCu-FN)	Parathion methyl	Peroxidase	11 pg/mL	-	96.5 % to 105.0 %	[76]
Pt/Co_3O_4	Thiram, Ziram	Peroxidase, Oxidase, Catalase, Superoxide dismutase	15.63 ng/mL, 1.03 µg/mL	-	95.33-101.60%	[77]

4.1.1. Strategic advantages of nanozyme-based colorimetric detection methods

The first strategic advantage of nanozyme-based colorimetric methods is inherent signal amplification for high sensitivity. As pesticides typically exist at very low concentrations, high sensitivity is essential for their detection. Nanozymes, like natural enzymes, act as catalysts, where a single particle can rapidly and repeatedly convert numerous chromogenic substrate molecules (e.g., 3,3',5,5'-tetramethylbenzidine, TMB).[78] This is a powerful mechanism that amplifies the minute initial signal caused by trace amounts of pesticides into a distinct color change visible to the naked eye. Because of catalytic amplification, nanozyme-based colorimetric assays afford lower limits of detection than their noncatalytic counterparts.[79] The second advantage is superior robustness and stability over natural enzymes. Traditional biosensors usually use the natural enzymes (for example AChE), which possess high specificity but suffer from inherent limitations of protein structure, making them susceptible to changes in external environmental conditions such as temperature, organic solvents, and pH.[23, 24] This reduces the shelf life of sensor and inhibits its direct application to real-world samples such as soil extracts or fruit surface. Conversely, nanozymes derived from stable inorganic materials such as metal oxides, metals, or carbon exhibit chemical and physical adaptability, preserving their catalytic activity even in extreme pH or higher temperature environments. This

View Article Online
DOI: 10.1039/D5TA09692H

dramatically extends the sensor's shelf life and provides strong field applicability, allowing for direct use on various real samples without the need for purification or complex pretreatment steps. Finally, there is excellent cost-effectiveness and design flexibility. Natural enzymes require complex biological expression and purification processes, leading to high production costs. Nanozymes can be mass-produced at a low cost through simple chemical synthesis methods, a condition highly favorable for developing low-cost, disposable strip-type diagnostic kits.[78] Furthermore, by precisely controlling the size, composition, morphology, and surface chemistry of the nanomaterials, it is possible to optimize their catalytic activity or easily introduce molecular recognition elements, such as aptamers that specifically bind to certain pesticide molecules, onto their surface.[46, 80] This tailor-made design capability signifies the limitless potential for developing high-performance sensors optimized for the target analyte of interest and forms the basis for the various innovative nanozymes discussed in this review. The subsequent sections will delve into the specific mechanisms through which these advantages are realized, categorized by the nature of the nanozyme-pesticide interaction.

4.1.2 Classification of nanozyme-based colorimetric sensors for pesticide detection

The most intuitive method in nanozyme-based colorimetric sensing uses the principle where the pesticide molecule itself interacts directly with nanozyme to alter its intrinsic catalytic function. This process is substantially efficient as it eliminates the need for auxiliary enzymes or intermediate steps, leading to faster and simpler analytical systems.[81] The direct interaction approach can be further classified into two primary modes: modulation of separate chromogenic substrate's oxidation, and direct enzymatic conversion of pesticide itself into signal molecule. Modulation of chromogenic substrate oxidation is the most widely explored

View Article Online
DOI: 10.1039/D5TA09692H

direct interaction pathway. Intrinsic enzyme-like activity (for example oxidase or peroxidase) nanozyme's is utilized to catalyze the oxidation of chromogenic substrate like TMB.[49, 74, 82] The target pesticide molecule then interact directly with nanozyme, acting as either an enhancer or an inhibitor of this catalytic activity, leading to a assessable change in intensity of color. Indirect interaction mechanisms rely on a 'mediator' or 'byproduct', whose concentration is modulated by the presence of the pesticide, to regulate the nanozyme's activity. This approach can significantly expand the selectivity and design flexibility of the detection system by incorporating auxiliary enzymes that react with a specific class of pesticides or by utilizing characteristic chemical reactions of the pesticide.[46, 83] This strategy allows the highly efficient catalytic activity of nanozymes to be coupled with well-established biochemical recognition events. The most representative and widely adopted example is using the principle of AChE inhibition.[48, 53, 57, 62, 66, 67, 70, 76] Organophosphorus and carbamate pesticides are potent inhibitors that irreversibly bind to the active site of AChE, an essential enzyme for normal nerve signal transmission. By coupling this principle with a nanozyme system, highly sensitive sensors can be implemented. In this system, the key 'mediator' is thiocholine (TCh), which is produced from the hydrolysis of the AChE substrate, and acetylthiocholine (ATCh). The concentration of TCh mediators is inversely proportional to pesticide concentration, which acts as a switch to control the nanozyme's activity.

4.1.2.1 Detection mechanisms based on direct interaction

Typically, colorimetric sensors based on the simple direct mechanism exhibit a 'turn-off' response due to direct inhibition by the pesticide. In this mode, the pesticide binds to the nanozyme's active sites or blocks substrate access, causing a decrease in the colorimetric signal.

View Article Online
DOI: 10.1039/D5TA09692H

In 2024, *Yan et al* designed bio-inspired glutathione-iron hybrid (GSH-Fe) nanozyme to detect the fungicide thiram. Thiram molecules, containing sulfur atoms, exhibit strong affinity for the iron centers of the nanozyme, leading to surface passivation and inhibition of its peroxidase-like activity. This system achieved a low detection limit of 0.3 μg/mL within a linear range of 0.3-10 μg/mL. Also, they achieved a recovery rate of 92.4% to 106.9%. To improve stability and practicality, the nanozyme was immobilized in a hydrogel, and a simple smartphone with ImageJ software was used for quantification, demonstrating its potential for on-site analysis of fruit juice samples.[50] In 2025, *Zhang et al.* designed a ternary MOF, ZnCo-ZIFs@MIL-101(Fe), and engineered the designed material with multiple metal sites to detect glyphosate. The principle relies on the coordination of glyphosate's phosphonic acid group with these exposed metal active sites, hindering TMB oxidation. This sensor demonstrated a wide linear range of 0-1 μg/mL and an LOD of 75 ng/mL. Its utility for on-site applications was proven by integrating it into a smartphone and paper-based microfluidic chips (μPAD) for analyzing samples.[59] Advanced 2D materials have also shown great promise. MQDs@CuNi, a composite of MXene quantum dots (MQDs) and a copper-nickel bimetal, and MQDs-NiCoP/NF, an urchin-like nickel-cobalt phosphide structure modified with MQDs, both function by the principle of glyphosate directly binding to their active sites and inhibiting their peroxidase-like activity (Fig. 1a). These systems achieved remarkably low detection limits of 1.06 μM, respectively, showcasing their potential for highly sensitive trace analysis.[72] In 2023, *Zhang et al.*, used Cu-doped carbon nanozyme to detect the fungicide thiophanate-methyl. The interaction between the pesticide's sulfur and nitrogen atoms and the copper active sites on the nanozyme surface inhibits its oxidase-like activity, resulting in a 'turn-off' response with a low LOD of 0.04 μg/mL.[73] Li *et al*. developed a bioinspired laccase-mimicking catalyst, designated as GSH-Cu, by simulating the copper active sites and spatial amino acid

View Article Online
DOI: 10.1039/D5TA09692H

microenvironment of natural enzymes. This nanozyme, synthesized through the coordination of Cu^{2+} with glutathione (GSH) peptides, exhibits catalytic functions that conform to the Michaelis-Menten kinetics of natural laccase (Fig. 1b). The sensing mechanism is based on a pesticide detection mechanism through a direct interaction method, where the catalytic activity of the GSH-Cu complex is triggered for inhibition by thiram. Specifically, the coordination between sulfur (S) and copper (Cu) atoms disrupts the surface structure of the catalyst and leads to the formation of copper nanoparticles, a process characterized as catalytic inhibition (Fig. 1c). The developed sensor demonstrated outstanding performance with a laccase (LOD) of 2.00 ng/mL in solution, covering a linear range from 2.5 to 250 ng/mL. This system proved highly effective for the sensitive detection of pesticides in real food samples, such as fruit juices and environmental water. To determine sensing mechanism, absorption spectra were measured to ascertain the coordination between copper ions and thiram (Fig. 1d).[71]

View Article Online
DOI: 10.1039/D5TA09692H

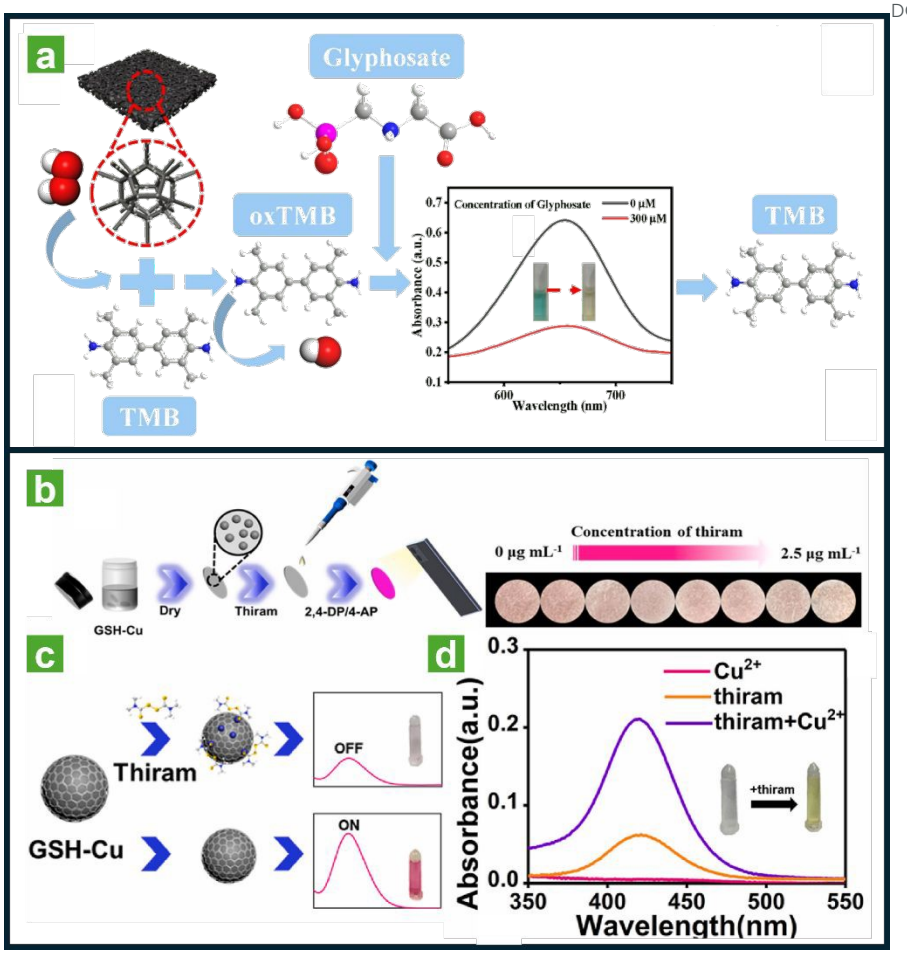


Fig. 1. Pesticide detection mechanism through direct interaction method. (a) Diagrammatic depiction of the colorimetric sensing of glyphosate facilitated by 0.5 MQDs-NiCoP/NF nanozymes. Reproduced from reference[72] with permission from Elsevier, copyright 2025. (b) Conceptual design of a paper-based analytical platform for the monitoring of thiram residues. (c) Illustrative representation of the catalytic inhibition of GSH-Cu complexes triggered by thiram. (d) UV–vis electronic absorption profiles of Cu^{2+}, thiram, and the resulting Cu^{2+}-thiram coordination complex. Reproduced from reference[71] with permission from Elsevier, copyright 2022.

View Article Online
DOI: 10.1039/D5TA09692H

Conversely, 'Turn-on' sensors based on direct enhancement are highly advantageous for achieving superior sensitivity due to their inherently low background signal. In 2024, *Xu et al.* developed an iron-based MOF, Fe@PCN-224 NCs, whose peroxidase-like activity is markedly enhanced in the presence of the fungicide propiconazole. This is interpreted as propiconazole inducing a conformational change in the MOF structure that improves TMB substrate accessibility to the active iron-porphyrin sites. This 'turn-on' sensor achieved an impressive LOD of 8 nM over a linear range of 0.03-90 μM in vegetable samples, demonstrating a rare case of analyte-induced activation.[49] In 2025, *Liu et al.* developed a copper-based MOF, Cu-BDC-NO_2, was rationally designed by tuning the ligand with an electron-withdrawing nitro group, which enhanced its laccase-like activity. This activity was further promoted by glyphosate, leading to a 'turn-on' response with an LOD of 37 ng/mL. This design ensures that the nanozyme's activity is restored only in the presence of the target pesticide, which displaces the aptamer from the nanozyme surface, thus securing overwhelming selectivity.[54] The most representative phosphatase-like activity was exhibited by Zr-based MOFs. Nanozyme developed by *Zhu et al.* in 2025, directly cleavage the phosphoester bond of the paraoxon pesticide, converting the colorless paraoxon into the distinctly yellow-colored p-nitrophenol. The Zr_6 clusters within the MOF structure act as potent Lewis acid sites, activating water molecules for a nucleophilic attack on the phosphorus center of the pesticide, thereby cleaving the ester bond. This constitutes a perfect 'turn-on' system where the presence of the pesticide directly generates a color signal from 'none' to 'some', achieving a LOD of 0.195 μM. As this method is not based on redox reactions, it can fundamentally exclude interference from common redox-active substances in the sample, leading to very high reliability and analytical accuracy. This method signifies a paradigm shift from the indirect signal generation to direct

View Article Online
DOI: 10.1039/D5TA09692H

transformation of analyte, offering a highly robust and specific platform for the analysis pesticide.[64]

4.1.2.2. Detection mechanisms based on indirect interaction

In fact, indirect detection methods, inspired by the principle of AChE inhibition, are more traditional and have been researched more extensively than direct detection methods. Wang *et al*. (2024) applied molecular imprinting approach on Mn@NC nanozyme with phoxim as template molecule. This method created molecularly imprinted sites on the surface of nanozyme that precisely fit phoxim molecules, allowing it to detect selectively the phoxim while excluding other pesticides with similar structures. Fabricated sensor recorded a wide linear range of 5-1000 ng/mL and an LOD of 1.27 ng/mL in colorimetric approaches, proving that molecular imprinting is an effective method for simultaneously enhancing selectivity and sensitivity.[60]

View Article Online
DOI: 10.1039/D5TA09692H

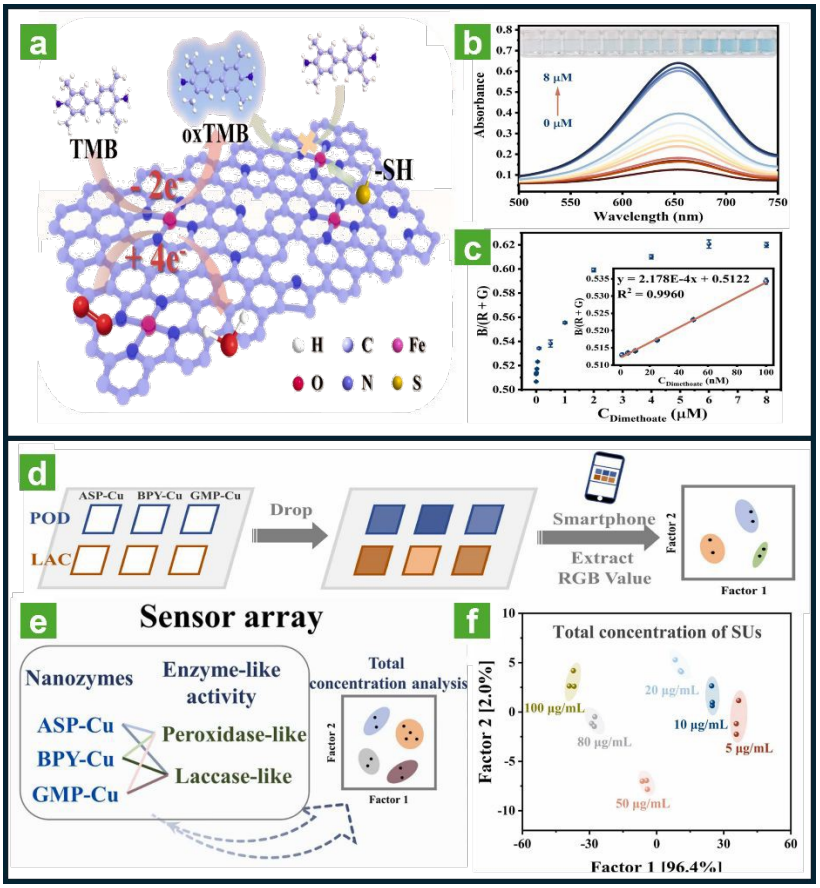


Fig. 2. Pesticide detection mechanism through indirect interaction method. (a) Conceptual diagram illustrating the oxidase-mimicking behavior of Fe-N/C SAzymes and the inhibitory effect of mercapto-containing molecules on their catalytic activity. (b) UV–vis absorbance profiles of the colorimetric assay at various dimethoate concentrations (0 to 8 μM); the inset provides the corresponding visual color transitions. (c) Analytical correlation between the B/(R+G) color intensity ratio and dimethoate levels, with the inset displaying the established linear regression model. Reproduced from reference[70] with permission from Elsevier, copyright 2024. (d) Illustrative schematics of paper-based sensor arrays that leverage enhanced multienzyme-like catalytic activities. (e) Development of a six-channel sensor array based on the laccase- and peroxidase-mimicking activities of ASP-Cu, BPY-Cu, and GMP-Cu for the selective detection of sulfonylureas. (f) Linear discriminant analysis score plot for the

View Article Online
DOI: 10.1039/D5TA09692H

qualitative classification of sulfonylurea (SU) mixtures across a concentration range of 5 to 100 μg/mL. Reproduced from reference[52] with permission from Elsevier, copyright 2024.

Zhang et al.[70] developed a sensor that indirectly detects pesticides using an Fe-N/C single-atom nanozyme (SAzyme). The sensor's operating principle is based on an oxidase-like reaction in which the Fe-N/C nanozyme converts colorless TMB into the blue-colored oxidized TMB (oxTMB). In this process, an enzyme called acid phosphatase (ACP) is introduced, which hydrolyzes L-ascorbic acid-2-phosphate (AAP) to produce ascorbic acid (AA), an inhibitor of the color reaction (Fig. 2a). In the absence of pesticides, the ACP enzyme is active and produces AA, which blocks the color reaction, causing the solution to remain colorless. Conversely, when a pesticide is present, it inhibits the activity of the ACP enzyme, preventing the production of AA. As a result, the Fe-N/C nanozyme is free to oxidize TMB, turning the solution blue (Fig. 2b). Thus, the presence of the pesticide determines the expression of the blue color, operating in a 'turn-on' fashion. Through this indirect detection method, the sensor demonstrated excellent performance. Based on the pesticide dimethoate, it achieved a very low LOD of 0.4177 nM (Fig. 2c). Additionally, in recovery experiments, which indicate accuracy in real fruit and vegetable samples, it showed high reliability with results ranging from 95.01% to 103.94%.[70] Additionally, Tian et al. reported a unique mechanism that amplifies a signal through indirect interaction. In this study, three copper-based nanozymes ASP-Cu, BPY-Cu, and GMP-Cu-were utilized to selectively detect sulfonylurea (SU) pesticides (Fig. 2d). The core principle of this sensor is based on the phenomenon where sulfonylurea pesticides, instead of directly inhibiting the enzyme-like activities (laccase-like and peroxidase-like) of the nanozymes, actually enhance their activity. This is a 'turn-on' method where the pesticide

View Article Online
DOI: 10.1039/D5TA09692H

molecule indirectly promotes the nanozyme's catalytic reaction to generate a stronger colorimetric signal, thereby detecting the pesticide's presence (Fig. 2e). This sensor achieved a LOD of 0.03 μg/mL for the total concentration of sulfonylurea pesticides and demonstrated high accuracy and reliability with a recovery rate in real water samples ranging from 91.53% to 103.5% (Fig. 2f).[52]

The PtPdNPs@g-C_3N_4 nanozyme that developed by *Shen et al.* in 2023, has oxidase-like activity, which is inhibited by the thiol group of the thiocholine produced in the absence of pesticides. In contrast, when a pesticide is present, AChE is inhibited, no thiocholine is produced, and consequently, the nanozyme's activity is 'turned on', resulting in a strong colorimetric signal. This sensor showed an LOD of 83 pg/mL in colorimetric approaches, demonstrating a sensitive indirect detection route.[55] Similarly, $PtCu_3$ alloy nanocrystals developed as high-sensitivity 'turn-on' sensors for pesticides based on the AChE inhibition principle. It achieved impressive LODs of 0.05 ng/mL to trichlorfon, and demonstrated the feasibility of smartphone-based quantification for on-site analysis.[66] The triple composite PB@Fe-COF@Au were also developed as ‘turn on’ sensor for trichlorfon detection. This system is particularly noteworthy for its "triplet peroxidase-like activity" where the Prussian blue, COF, and Au components all contribute to signal generation, creating a highly amplified response. This multi-component design capitalizes on the high catalytic activity of PB and Au, coupled with the large surface area and analyte-capturing ability of the COF, to create a highly efficient cascade reaction.[65]

View Article Online
DOI: 10.1039/D5TA09692H

Regulation of nanozyme activity by byproducts generated from the chemical reaction of the pesticide itself is also an effective strategy. This method can enhance selectivity by utilizing chemical reactions unique to a specific pesticide, leading to AChE-free assays, which avoids the use of unstable natural enzymes. In 2024, *Zhu et al.* developed CeO_2@NC nanozyme, also utilizes this principle, promoting the hydrolysis of carbosulfan and using the generated SH group in acidic condition to modulate its activity, achieving an LOD of 3.3 nM. This approach is particularly valuable as it builds specificity into the system based on the unique chemistry of the target analyte, rather than relying solely on a general enzymatic inhibition mechanism.[58] Sometimes, multiple steps of indirect interaction are combined to create more sophisticated sensing cascades. In 2024, *Liu et al.* engineered copper-based MOF NH_2-CuBDC to detect the insecticide chlorpyrifos. In this system, chlorpyrifos inhibits AChE activity, and the resulting lack of thiocholine production alters its interaction with copper ions (Cu^{2+}), which in turn modulates the peroxidase-like activity of the nanozyme. Designed sensor achieved an LOD of 1.57 ng/mL in colorimetric method, showcasing how multiple equilibria can be coupled for sensitive detection.[48] Another cascade system was built using the FeCoCu flower-like structure, which could be switched between 'turn-off' and 'turn-on' modes. In one mode, AChE inhibition prevented the production of the inhibitory thiocholine. In another mode, the product of AChE (choline) was further converted by choline oxidase (ChOx) to produce H_2O_2, the substrate for the nanozyme's peroxidase activity, leading to a 'turn-on' signal upon AChE inhibition. They achieve LOD of 0.11 and 0.13 ng/mL and recovery rate 96.5-105.0% and 94.0-105.0% in AChE method and ChOx single enzyme method. Thus, while indirect mechanisms based on mediators or byproducts may require more complex system designs, they can be used as potential strategy for enhancing sensor selectivity or diversifying signal transduction pathways by incorporating specific chemical reaction routes into the design.[76]

View Article Online
DOI: 10.1039/D5TA09692H

4.2. Nanozymes for the fluorescent detection of pesticides

Fluorescence detection is currently recognized as one of the most sensitive and selective analytical techniques in the field of pesticide analysis. It plays a vital role in food safety and environmental monitoring, particularly due to its high sensitivity, real-time monitoring capabilities, and potential for visual discrimination. The emergence of nanozyme-based fluorescent detection systems has brought innovative changes to this field. This is because they effectively overcome the fundamental limitations of traditional natural enzyme-based systems while further amplifying the inherent advantages of fluorescence detection. The integration of nanozymes with fluorescent detection mechanisms is more than a simple combination of two technologies; through synergistic effects, it is fundamentally changing the paradigm of pesticide detection. These systems are widely applied for the detection of organophosphorus pesticides (OPs), carbamate pesticides, glyphosate, neonicotinoid pesticides, and various other pesticide compounds, providing tailored detection strategies suited to their respective chemical properties and mechanisms of action.[2, 84, 85] The core working principle of nanozyme-based fluorescence detection is found on the complex and sophisticated interaction between target pesticide and the nanozyme, which ultimately induces a quantitative change in the fluorescent signal. This interaction is not a simple one-dimensional reaction but occurs through a multi-step mechanism at the molecular level. Key mechanisms that work in combination include enzyme activity modulation, the inner filter effect (IFE), Förster resonance energy transfer (FRET), photoinduced electron transfer (PET), aggregation-induced emission (AIE) and electron exchange (EE). Each of these mechanisms is selectively activated depending on the molecular structure of a specific pesticide and the physicochemical properties of the nanozyme

View Article Online
DOI: 10.1039/D5TA09692H

system. This enables the construction of detection platforms that can simultaneously achieve extremely high specificity and sensitivity.[86, 87]

The fluorescence detection mechanism based on enzyme activity inhibition and modulation is one of the most extensively studied and practical approaches, demonstrating excellent performance, particularly in the detection of organophosphorus and carbamate pesticides. The core of this method is that pesticides specifically inhibit the activity of key biological enzymes, such as AChE. This inhibition modulates the catalytic activity of a nanozyme through an elaborately designed multi-step cascade reaction, ultimately inducing a quantitative change in the fluorescent signal. For example, an organophosphorus pesticide forms a covalent bond with the serine residue in the active site of AChE, irreversibly inhibiting the enzyme. This blocks the hydrolysis of ACh. Consequently, the subsequent oxidation of choline to hydrogen peroxide (H_2O_2) by choline oxidase (ChOx) is reduced. This ultimately leads to decreased catalytic activity of a peroxidase-like nanozyme, which alters the oxidation state of a fluorescent substrate and results in a measurable change in the fluorescence signal. The primary advantage of such a cascade reaction system is its inherent signal amplification effect: a single pesticide molecule can inhibit numerous enzyme molecules, and each enzyme can, in turn, process a multitude of substrate molecules.[88, 89] Fluorescence detection systems based on direct interaction and molecular recognition operate on a mechanism where a pesticide interacts with a nanozyme through direct chemical bonding or physical adsorption. This interaction alters the nanozyme's structural and electronic properties, which in turn directly leads to a change in its fluorescence characteristics. In this mechanism, specific chemical functional groups on the pesticide molecule such as sulfur, phosphorus, and halogen atoms, or aromatic ring structures

View Article Online
DOI: 10.1039/D5TA09692H

form various intermolecular interactions with the active sites or metal centers on the nanozyme's surface, including hydrogen bonds, coordination bonds, π-π stacking, and van der Waals forces. A particularly interesting example is when a sulfur-containing pesticide like malathion forms a strong Ag-S coordination bond with a silver nanoparticle-based nanozyme. This alters the nanozyme's surface electronic structure, which selectively inhibits its oxidase-like activity and induces a change in the fluorescence signal associated with the oxidation of TMB.[90] The greatest advantages of this direct interaction mechanism are that high specificity can be achieved without using any biological enzymes and that it demonstrates stable performance even in complex matrices.[49, 91]

The FRET based fluorescence detection mechanism is a highly sophisticated and sensitive method that utilizes non-radiative transfer of energy between a fluorescence acceptor and a donor. In these systems, a nanozyme plays the role of either the donor or the acceptor, and the presence of a target pesticide dynamically alters the FRET efficiency, which induces an increase, decrease, or spectral shift in the fluorescence intensity. For FRET to occur effectively, several conditions must be met, there must be significant spectral overlap between the donor's emission spectrum and the acceptor's absorption spectrum, the distance between two molecules must be within the 1-10 nm range, and the relative orientation between the transition dipole moments of the donor and acceptor must be appropriate.[92, 93] These conditions can be precisely controlled in nanozyme-based systems in response to the presence of a pesticide. For instance, nanozymes with fluorescent properties such as gold nanoparticles, graphene quantum dots (GQDs), or MOFs doped with rare-earth elements can be utilized as key components in these FRET systems.[94] The IFE is a phenomenon in which the observed fluorescence intensity

View Article Online
DOI: 10.1039/D5TA09692H

decreases because the emission or excitation light of a fluorophore is absorbed by an absorber present in the solution. In nanozyme-based systems, this mechanism involves the products or intermediates of a catalytic reaction acting as the absorber to modulate the fluorophore's signal. A typical example is when a peroxidase-like nanozyme oxidizes a colorless substrate, such as TMB, to produce a colored oxidation product (e.g., oxTMB). This product exhibits strong absorption in a specific wavelength region, effectively quenching the signal of a fluorophore that emits fluorescence in the same or a similar wavelength region. A unique advantage of IFE-based detection systems is that, unlike FRET, physical proximity between the fluorophore and the absorber is not essential. This provides greater choice in system design and enables various combinations of nanozymes and fluorophores.[95-97] The PET mechanism is a highly sophisticated and sensitive detection method that utilizes the phenomenon of fluorescence quenching or enhancement, which occurs when a fluorophore in a photoexcited state exchanges electrons with an electron donor or acceptor. In the PET process, an electron from the excited fluorophore is transferred to a nearby electron acceptor (quencher), or conversely, an electron from a donor is transferred to the highest occupied molecular orbital (HOMO) of the fluorophore, leading to the suppression of fluorescence emission.[98] In nanozyme-based systems, the PET mechanism is widely observed, particularly in gold nanoclusters (AuNCs), carbon quantum dots (CQDs), and various fluorescent MOFs, where the presence of a pesticide modulates this electron transfer process to induce a change in the fluorescent signal. For instance, in the BSA-stabilized gold nanoclusters (BSA-AuNCs), it has been shown that PET quenchers such as ascorbic acid, mercury ions, and dopamine not only quench fluorescence but can also simultaneously modify nanoclusters' intrinsic peroxidase-like activity. This attribute can be utilized to develop dual-mode (colorimetric and fluorescent) sensing systems.[99] PET quenchers do not inherently inhibit nanozyme activity. In certain circumstances, Cu^{2+} or

View Article Online
DOI: 10.1039/D5TA09692H

specific cyanine dyes, can augment the peroxidase-like activity. By effectively utilizing this feature, it is possible to design highly selective and sensitive pesticide sensing systems.[100, 101] The electron exchange mechanism elucidates the change in fluorescence characteristics by direct transfer of electrons between a target molecule and a nanozyme, a phenomenon closely related to the surface quenching effect. This method involves defect sites or metal ions on the nanozyme surface functions such as electron acceptors or donors, facilitating direct electron transfer with a fluorophore, hence causing either amplification or quenching of fluorescence. The electron exchange mechanism is highly sensitive to surface state and electronic structure of nanozyme. Consequently, its direction and efficiency can vary substantially depending on the nanozyme's size, composition, shape, and surface functionalization. The AIE process is an innovative detection approach that employs a unique phenomenon. Unlike conventional fluorophores that undergo fluorescence quenching in an aggregated state, AIE-active compounds (AIEgens) demonstrate pronounced fluorescence upon aggregation. This phenomenon is attributable to the limitation of intramolecular rotational effects. The underlying principle is that when molecules aggregate, their internal rotations are physically restricted. This restriction suppresses non-radiative energy dissipation pathways, which in turn enhances fluorescence emission. In nanozyme-based AIE systems, the catalytic activity of a nanozyme can control the aggregation state of AIE molecules. Conversely, a target pesticide can alter the aggregation state of an AIE-active nanozyme (AIEzyme), thereby inducing a change in the fluorescence signal. For instance, an AIEzyme with organophosphorus hydrolase (OPH)-like activity can hydrolyze an organophosphorus pesticide. During this process, its own fluorescence is quenched, enabling a self-reporting function. This allows for the specific and sensitive detection of nerve agents and pesticides.[102] Table 2 shows the comparative analysis of nanozyme-based fluorescent sensors for pesticide detection.

View Article Online
DOI: 10.1039/D5TA09692H

Table 2. Comparative analysis of nanozyme-based fluorescent sensors for pesticide detection

Nanozyme	Pesticides	Enzyme activity	LOD	Reaction time	Recovery rates	Ref.
66-IS-Zn	Profenofos, phoxim	phosphatase		30 min		[103]
Cu-BDC-NH_2	Malathion, Dicofol, Fenvalerate, Pirimicarb, Dimethoate, Phosmet	Peroxidase		15 min		[104]
MB/COF@MnO_2	Dichlorvos, Omethoate, Trichlorfon, Chlorpyrifos, Chlorfenvinphos	Oxidase	83 pg/mL	30 min	97.8 %-105 %	[105]
PtPdNPs@g-C_3N_4	Dimethoate, Phosphine acetyloxalamine	oxidase	33 pg/mL	20 min	95.78–104.34 %	[55]
ASP-Cu	Metsulfuron, Rimsulfuron, Sulfosulfuron, Halosulfuron-methyl	Peroxidase		15 min	-	[56]
JLU-MOF22	Benfuracarb	Oxidase	76 ng/mL	1 min	98.8 to 102.55 %	[106]
Zr-TCPE	Paraoxon	Phosphatase	48.99 ng/mL	30 min	96.1–115.0%	[64]
Fe-N/C single-atom	Malathion	Oxidase	0.139 ng/mL	10 min	98.6%-105.4%	[67]
NH_2-CuBDC	Chlorpyrifos	Peroxidase	2.33 ng/mL	10 min	103.19%	[48]
NH_2-MIL-101(Fe)	Glyphosate	Peroxidase	3.16 ng/mL	15 min	92.4 %-115.6 %	[107]
Cu-MIL-53(Fe)-2	Malathion	Peroxidase	42.62 ng/mL	15 min	96.65 %-108.92 %	[108]
MQDs@CoO_x-300	Profenofos	Peroxidase	0.254 ng/mL	10 min	94.7 %-104 %	[109]

View Article Online
DOI: 10.1039/D5TA09692H

Cu–BH	Thiophanate methyl	oxidase	10.27 ng/mL	30 min	91.5 %-93.5 %	[110]
AuNEs	Chlorpyrifos, Dimethoate, Methyl paraoxon	Peroxidase	7 ng/mL, 14 ng/mL, 16 ng/mL	25 min		[111]
MQDs@CuNi	Glyphosate	Peroxidase	0.12 pg/mL	10 min	97.4 %-111.2 %	[68]
CTEzyme	Methidathion	Peroxidase	0.625 ng/mL	20 min	97.3%-105.7 %	[112]
Zr-MOF	Paraoxon	Phosphatase	1.67 ng/mL	60 min	99.8 %-100.6 %	[113]

4.2.1. Strategic advantages of nanozyme-based fluorescent detection methods

The strategic benefits of nanozyme-based fluorescence detection approaches stem from the synergistic integration of fluorescence technology and the distinctive characteristics of nanozymes, which are crucial for attaining significant enhancements in pesticide detection. These advantages extend beyond the general benefits of nanozymes in fluorescence detection; they encompass distinctive characteristics in the modulation, amplification, generation, and detection of the fluorescent signals, providing substantial performance improvements over conventional fluorescent or colorimetric techniques. A major strategic advantage is the capacity to attain exceptionally high sensitivity via catalytic signal amplification. Traditional fluorescence detection approaches typically depend on a 1:1 interaction between a target molecule and a fluorophore; however, in nanozyme-based systems, a single target molecule can influence the catalytic efficiency of a nanozyme to transform multiple fluorescent substrate molecules, thereby offering a natural signal amplification phenomenon. For instance, during the reaction in which a peroxidase-like nanozyme oxidizes a non-fluorescent substrate such as terephthalic acid (TA) to yield highly fluorescent 2-hydroxyterephthalic acid (2-HTA),

View Article Online
DOI: 10.1039/D5TA09692H

inhibition of the enzyme by one specific pesticide molecule results in the diminished production of numerous fluorescent molecules, thereby attaining a significantly elevated signal amplification ratio.[114] This catalytic amplification significantly enhances the signal-to-noise ratio, facilitating the precise detection of trace levels of pesticides in complex matrices. Moreover, the catalytic efficacy of nanozymes facilitate enhanced signal amplification by fine-tuning parameters such as temperature, pH, and reaction duration, a distinctive advantage unattainable with conventional fluorescence techniques. A study involving Cu-BH nanozymes indicated that molecules improved the catalytic activity of the nanozyme, intensifying the fluorescent signal and attaining a remarkably low detection limit. This catalytic signal amplification facilitates a linear enhancement in fluorescence intensity, markedly enhancing the accuracy and precision of quantitative evaluation.[110]

Nanozyme-based fluorescence detection approaches offer distinct advantages for real-time monitoring of pesticides. Because the fluorescent signal can be assessed instantly and the nanozyme's catalytic reaction proceeds continuously, which enables real-time monitoring of temporal variations in pesticide concentration. This is a significant advantage compared to traditional detection methods that only provide static end-point analysis and can be utilized to monitor pesticide degradation processes or their behavior in the environment. Furthermore, by analyzing the nanozyme's catalytic reaction kinetics, information about the pesticide's inhibition mechanism can be obtained, providing valuable data for distinguishing between different types of pesticides or their mechanisms of action. The rapid response time of fluorescence detection is a decisive advantage in urgent food safety inspections and on-site monitoring, with most systems providing results within a few to ten minutes.[115] In a glyphosate detection system using Co_3O_4 nanozymes, for instance, detection is completed within 10

View Article Online
DOI: 10.1039/D5TA09692H

minutes, and the resulting color change remains stable for over 20 minutes, facilitating easy visual discrimination. This rapid response and signal stability meet the requirements for point-of-care testing and are also suitable for screening large volumes of samples.[116]

A unique advantage of nanozyme-based fluorescence detection is the ability to design a selective fluorescence response for specific pesticides by engineering the nanozyme's structure and surface functionalization. This is achieved through a ternary interaction system involving the fluorophore, the nanozyme, and the target molecule, where high specificity can be implemented by precisely controlling the properties of each component. For example, in aptamer-functionalized gold nanoparticles, binding with a specific pesticide (acetamiprid) selectively modulates the peroxidase-like activity of the nanoparticles, resulting in a fluorescent response that distinguishes it from other structural analogs. Furthermore, by controlling the pore structure or surface chemistry of the nanozyme, size selectivity or chemical selectivity can be achieved, enabling the selective detection of a target pesticide within a complex matrix.[117]

4.2.2 Classification of nanozyme-based fluorescent sensors for pesticide detection

The operating principles of nanozyme-based fluorescent pesticide detection systems can be classified according to the fundamental interaction among the target analyte (pesticide), the nanozyme catalyst, and the fluorescence signal-generating component. Nanozyme-based fluorescence pesticide sensors primarily rely on catalytic activity modulation, reaction by-product mediated fluorescence, or direct modulation of intrinsic fluorescence. This mechanistic classification forms the basis for determining key performance indicators such as sensor sensitivity, selectivity, and response speed, and it provides a theoretical foundation for

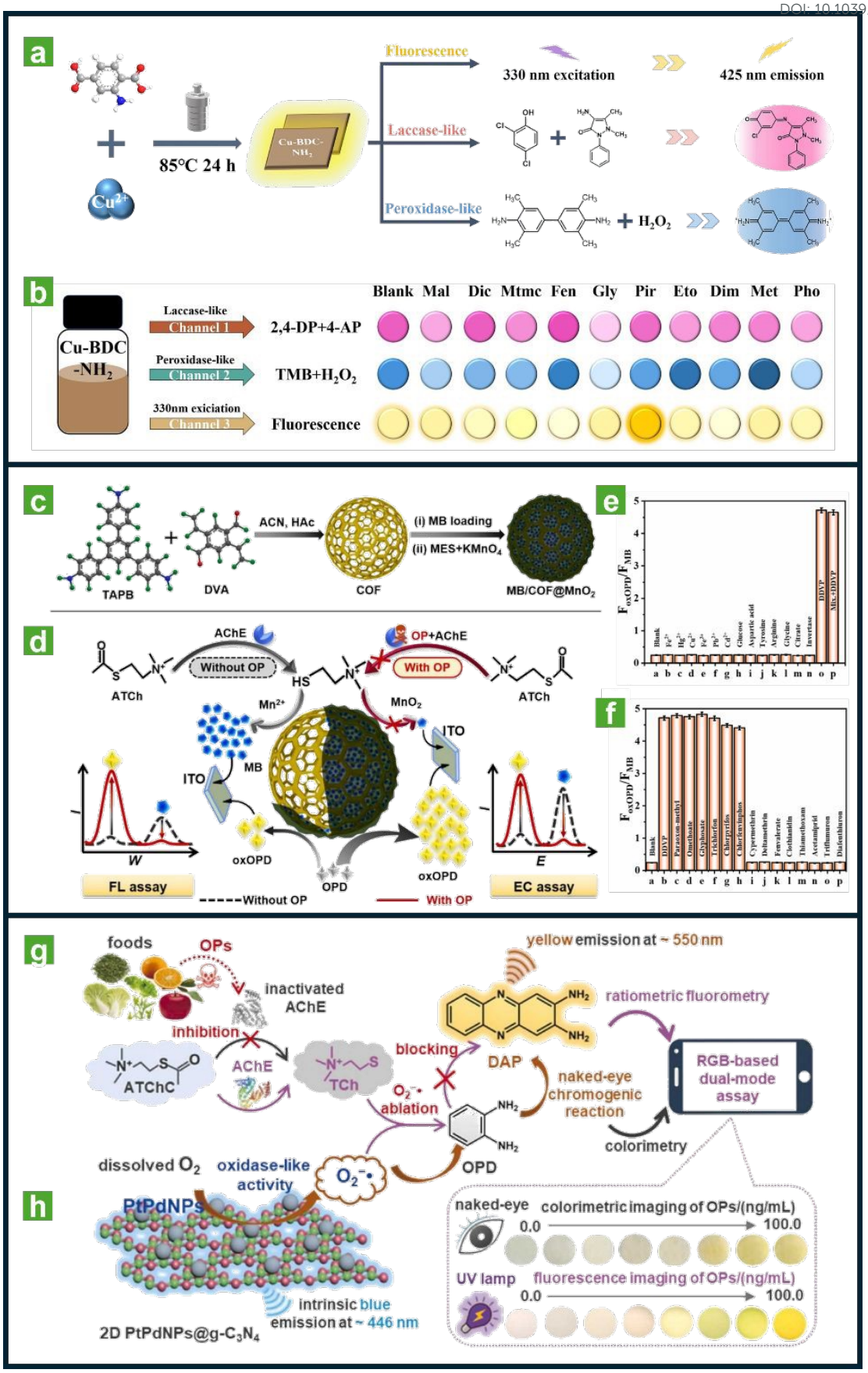
View Article Online
DOI: 10.1039/D5TA09692H

designing sensor platforms optimized for specific applications. To date, reported studies can be broadly divided into three dominant strategies. The first is a classic approach that relies on the indirect modulation of biological enzyme activity. In this method, the pesticide inhibits the activity of a specific biological enzyme, and the nanozyme acts as a signal transducer to convert this event into a fluorescent signal.[55, 104, 105] The second is the direct degradation of pesticides via the intrinsic catalytic activity of the nanozyme. This is a substantial approach, particularly mimicking the function of a phosphatase to directly hydrolyze the phosphate ester bonds of OPs.[64, 108] Further, an in-depth discussion of each classification will be presented below.

4.2.2.1. Enzyme activity inhibition by pesticides

Indirect detection through the modulation of biological activity of enzymes is the most thoroughly investigated and recognized method for detecting carbamate and organophosphorus pesticides. This methodology fundamentally relies on the biochemical mechanism through which these pesticides selectively impede the catalytic function of AChE, a crucial enzyme in the central nervous system. To convert this change in AChE activity into a quantifiable fluorescent signal, the sensor system employs a sophisticated enzymatic cascade reaction that includes a nanozyme. This approach directly reflects the in vivo toxicity mechanism of the pesticides, giving the detection results high biological significance. Furthermore, the multi-step enzymatic and nanozyme catalytic reactions provide inherent signal amplification, making it possible to achieve the high sensitivity required for trace analysis.[3, 118]

View Article Online
DOI: 10.1039/D5TA09692H



View Article Online
DOI: 10.1039/D5TA09692H

Fig. 3. Pesticide detection through enzyme activity inhibition mechanism. (a) Fluorescent Cu-BDC-NH_2 nanozyme demonstrating multienzyme-mimicking capabilities. (b) Implementation of a multi-responsive sensor array using Cu-BDC-NH_2 for the classification of pesticides across diverse concentration levels. The sensing platform is constructed by integrating laccase-mimicking, peroxidase-mimicking, and fluorescence-based detection pathways. Reproduced from reference[104] with permission from Elsevier, copyright 2024. (c) Schematic outlining the fabrication process of the Multifunctional COF composite (MCM). (d) Conceptual illustration of the dual-ratio enhanced FL/EC dual-mode sensor for OP analysis via target-regulated signal modulation. (e) FL ratio response of the dual-modal sensing platform toward a range of potential interferents (a–p: blank, Fe^{2+}, Hg^{2+}, Cu^{2+}, Fe^{3+}, Pb^{2+}, Cd^{2+}, glucose, aspartic acid, tyrosine, arginine, glycine, citrate, invertase, dichlorvos (DDVP), and their mixture) (f) Evaluation of FL ratios across various OPs and non-OP substances to demonstrate sensing selectivity. Reproduced from reference[105] with permission from Elsevier, copyright [2024]. (g) Design of a smartphone-integrated portable sensor based on 2D fluorescent oxidase-like PtPdNPs@g-C_3N_4 nanozymes for dual-mode (colorimetric and fluorescence) imaging of residual OPs. (h) Schematic illustration describing the oxidase-mimicking catalytic mechanism of the 2D PtPdNPs@g-C_3N_4 nanozyme. Reproduced from reference[55] with permission from Elsevier, copyright 2023.

The most representative system is a cascade reaction involving AChE and a peroxidase-like nanozyme. The operating principle of this system can be described in the following steps: (i) In the absence of a pesticide, AChE hydrolyzes its substrate, acetylcholine or acetylthiocholine, into choline or thiocholine. (ii) The generated choline is then oxidized by choline oxidase to

View Article Online
DOI: 10.1039/D5TA09692H

produce betaine and hydrogen peroxide. (iii) Finally, a nanozyme with peroxidase-like activity uses H_2O_2 as an oxidant to convert a fluorogenic substrate (e.g., Amplex red and terephthalic acid) into a product that emits strong fluorescence (e.g., Resorufin and 2-hydroxyterephthalic acid).[119] However, if the target pesticide is present in the system, the active site of AChE is irreversibly or reversibly blocked. This reduces the production of choline, which in turn leads to a sequential decrease in H_2O_2 generation and, ultimately, a reduction in the fluorescence signal's intensity. Therefore, the degree of fluorescence decrease shows a direct correlation with the concentration of the pesticide in the sample. In these signal transduction processes, materials such as Fe_3O_4, V_2O_5, noble metal nanoparticles (Au NPs, Pt NPs), and various carbon-based nanomaterials (graphene oxide, CQDs, etc.) have been successfully applied as peroxidase-like nanozymes.[67, 120] Additionally, in 2024, Song et al. presented an approach that analyzes enzyme activity inhibition patterns by utilizing multiple signals from a single material. In this study, a copper-based nanozyme (Cu-BDC-NH_2) with simultaneous laccase-like, peroxidase-like, and fluorescent properties was used. The detection mechanism of this sensor is based on the principle that different types of pesticides affect these three signals (two enzyme activities, one fluorescence) to varying degrees, generating a unique 'inhibition pattern' or 'signal fingerprint' (Fig. 3a). Through this multi-signal analysis, Song et al. successfully distinguished various types of pesticides down to a concentration of 1 μg/mL. Furthermore, when applied to real fruit and vegetable samples, the sensor demonstrated high reliability by identifying unknown samples with 100% accuracy (Fig. 3b).[104]

A 2024 study by Wen et al. applied an enzyme activity inhibition mechanism by developing a multifunctional covalent organic framework composite loaded with methylene blue and

View Article Online
DOI: 10.1039/D5TA09692H

coated with an MnO_2 nanozyme (Fig. 3c). Normally, thiocholine, produced when the enzyme AChE breaks down its substrate (ATCh), decomposes the MnO_2 coating, releasing the methylene blue signal molecule from inside. However, when OPs inhibit the activity of AChE, thiocholine is not produced, so the MnO_2 coating is maintained, acting as gate that blocks the release of MB (Fig. 3d). The dual-mode sensor demonstrated exceptional selectivity and robust anti-interference capability for OPs detection. High concentrations of diverse inorganic ions (such as Fe^{2+}, Hg^{2+}, and Cu^{2+}) and organic substances produced negligible variations in FL and electrochemical (EC) signals, whereas the presence of DDVP triggered significant responses (Fig. 3e). Furthermore, the platform's versatility was validated by its ability to accurately distinguish six typical OPs from representative non-OP pesticides. This high specificity is fundamentally attributed to the target-regulated, high-affinity inhibition of AChE by organophosphates (Fig. 3f). This sensor can detect dichlorvos based on fluorescence signal change, and achieved very low LOD of 0.083 ng/mL. Additionally, it showed excellent recovery rates in real vegetable and fruit samples, ranging from 95.2% to 104%.[105] Shen et al. applied the principle of enzyme activity inhibition by developing platinum-palladium nanoparticles combined with carbon nitride nanosheets (PtPdNPs@g-C_3N_4) (Fig. 3g). This nanozyme acts like an oxidase, converting surrounding oxygen into reactive oxygen species (O_2·). Normally, the enzyme AChE breaks down a substrate to produce TCh, which then removes the reactive oxygen species, preventing a fluorescence color change. However, when OPs inhibit the activity of AChE, thiocholine is not produced, allowing the reactive oxygen species to freely oxidize a substrate (OPD), which generates distinct fluorescence signals (Fig. 3h). This sensor demonstrated LOD for trichlorfon of 0.033 ng/mL via fluorescence methods, respectively, and recorded a high recovery rate of 95.78% to 104.34% in real food samples.[55]

View Article Online
DOI: 10.1039/D5TA09692H

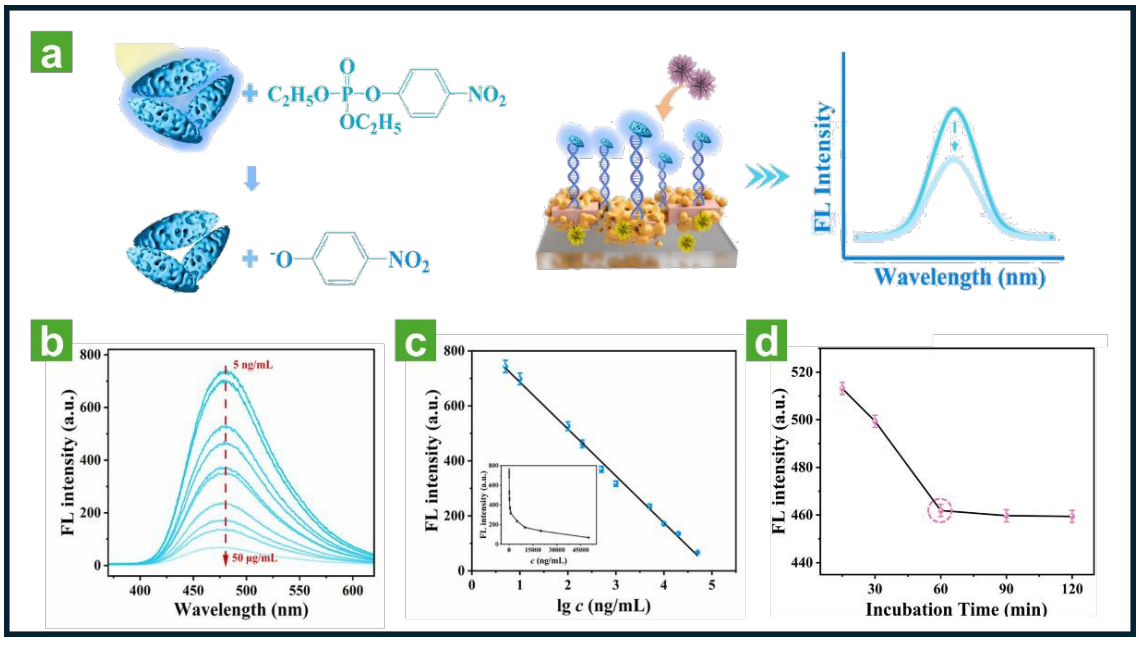
4.2.2.2. Byproduct mediated fluorescent detection

This approach utilizes the optical properties of the hydrolysis product. In this method, the nanozyme functions as a biochemical converter, transforming a non-optical pesticide substrate into a product with distinct optical characteristics. The most representative mechanism is fluorescence quenching via the inner filter effect. For example, certain OPs, such as methyl parathion, produce a chromophore called p-nitrophenol (PNP) upon hydrolysis. Under specific pH conditions, PNP exhibits a distinct UV-visible absorption spectrum. If a separate fluorophore (e.g., CQDs, organic dyes) whose excitation or emission wavelength overlaps with PNP's absorption band is introduced into the system, the PNP generated by the nanozyme-catalyzed reaction will absorb and extinguish the fluorophore's light. Consequently, a higher initial pesticide concentration produces more PNP, leading to a greater degree of fluorescence quenching. This relationship allows for the quantification of pesticides. A key advantage of this method is that it does not require physical binding or complex energy transfer processes between the nanozyme and the fluorophore, offering considerable versatility in system design. [121]

In 2026, Zhang et al developed a nanozyme-based sensor utilizing a byproduct-mediated fluorescent detection strategy for the sensitive monitoring of paraoxon. While the platform was designed as a dual-mode system, its optical detection specifically relied on a zirconium-based metal-organic framework (Zr-MOF), which served as a robust phosphatase-like nanozyme with intrinsic aggregation-induced emission (AIE) properties. Focusing on the fluorescence sensing mechanism, the approach utilizes a byproduct-mediated quenching process. Upon target exposure, the biomimetic catalytic sites of the Zr-MOF hydrolyze

View Article Online
DOI: 10.1039/D5TA09692H

paraoxon to generate p-nitrophenol (p-NP). This generated byproduct acts as a strong quencher, diminishing the intrinsic blue emission of the Zr-MOF via an Inner Filter Effect (IFE) (Fig. 4a). Based on this concentration-dependent fluorescence quenching, the platform yielded a limit of detection (LOD) of 1.67 ng/mL across a broad linear range of 5 ng/mL to 50 µg/mL (Fig. 4b). By mapping these spectral changes, a corresponding calibration plot was established, revealing a strong linear correlation ($R^2 = 0.995$) between the attenuated fluorescence intensity and the logarithm of the paraoxon concentration (Fig. 4c). Furthermore, to evaluate its practical applicability, the sensor was utilized to detect paraoxon in real-world samples. The fluorescence mode provided highly reliable and accurate performance, showing recoveries from 99.8% to 100.6% in tomato extracts and 99.5% to 100.4% in tap water matrices. Additionally, optimization studies demonstrated clear fluorescence quenching after 60 minutes, establishing this duration as the required incubation time for the sensor's optimal performance (Fig. 4d).[113]



View Article Online
DOI: 10.1039/D5TA09692H

Fig. 4. Pesticide detection mechanism through byproduct mediated fluorescence detection. (a) Diagrammatic of fluorescence sensing mechanism utilized byproduct-mediated quenching process, (b) Fluorescence emission spectra obtained at varying paraoxon concentrations (from 5 ng/mL to 50 µg/mL), (c) The corresponding calibration plot for the fluorescent assay, (d) Optimization of incubation time for the fluorescence emission of the sensor. Reproduced from reference[113] with permission from Elsevier, copyright 2026.

4.2.2.3. Modulation of intrinsic nanozyme fluorescence

This approach is a self-reporting detection method that works by changing the nanozyme's own fluorescence. The most ideal and streamlined system uses a self-reporting nanozyme, which acts as both catalyst and fluorescent signal material at the same time. In this approach, the nanozyme has intrinsic fluorescence, like protein-stabilized gold nanoclusters or certain MOFs. When a pesticide molecule binds to the active site of one of these fluorescent nanozymes and is hydrolyzed, it directly changes the nanozyme's electronic structure or surface ligand environment. For instance, the binding of the substrate might activate a non-radiative relaxation pathway, or the release of the product could alter the charge state of the fluorophore core. This local environmental shift immediately leads to a decrease or increase in the nanozyme's own fluorescence intensity, allowing for pesticide detection without any external source. This self-reporting mechanism is a game-changer because the reaction and signal generation are directly linked within a single entity, leading to fast reaction times and a very simple system design.[122, 123]

View Article Online
DOI: 10.1039/D5TA09692H

A key example of the direct pesticide quantification method is the 66-IS-Zn MOF nanozyme developed by Huang *et al*. (2025). This innovative approach introduces biomimetic zinc active sites into a UiO-66 framework to directly hydrolyze pesticides. This nanozyme directly cleaves the P-O bond of pesticides, producing phosphate ions and alcohol derivatives, all without the need for biological enzymes like AChE. During this process, a change in the ligand-to-metal charge transfer within the MOF structure leads to a change in fluorescence intensity (Fig. 5a). The system achieved a detection limit of 0.1-10 nM for methyl parathion, chlorpyrifos, and diazinon, with a response time of less than 10 minutes. A 3-channel sensor array even makes it possible to distinguish between multiple pesticides at the same time. Its practicality was confirmed with a recovery rate of over 90% in real agricultural samples, and it showed remarkable stability, maintaining over 90% of its activity after more than 100 reuses. This is a perfect example of an all-in-one platform where the nanozyme both degrades the pesticide and generates the detection signal, showcasing the core advantages of the direct degradation method with simple, enzyme-free system and broad operating conditions (Fig. 5b).[103] Zhu et al. (2025) proposed a method for detecting a specific OPs, paraoxon, utilizing a Zr-based MOF termed an 'AIEzyme.' This AIEzyme hydrolyzes paraoxon to produce yellow p-nitrophenol. This product induces a dual signal by simultaneously changing the solution's color (a colorimetric 'On' signal) while quenching the AIEzyme's own strong blue fluorescence via an inner filter effect (a fluorometric 'Off' signal) (Fig. 5c). The sensor exhibited excellent detection limits of 0.178 μM (colorimetric) and 0.195 μM (fluorometric), demonstrating its reliability with high recovery rates ranging from 96.1% to 115.0% in real samples (Fig. 5d, e). While this study is very similar to the previously discussed research case, its focus is on the precise quantitative analysis of a single pesticide, paraoxon, rather than on discriminating and identifying multiple pesticides (Fig. 5f).[64]

View Article Online
DOI: 10.1039/D5TA09692H

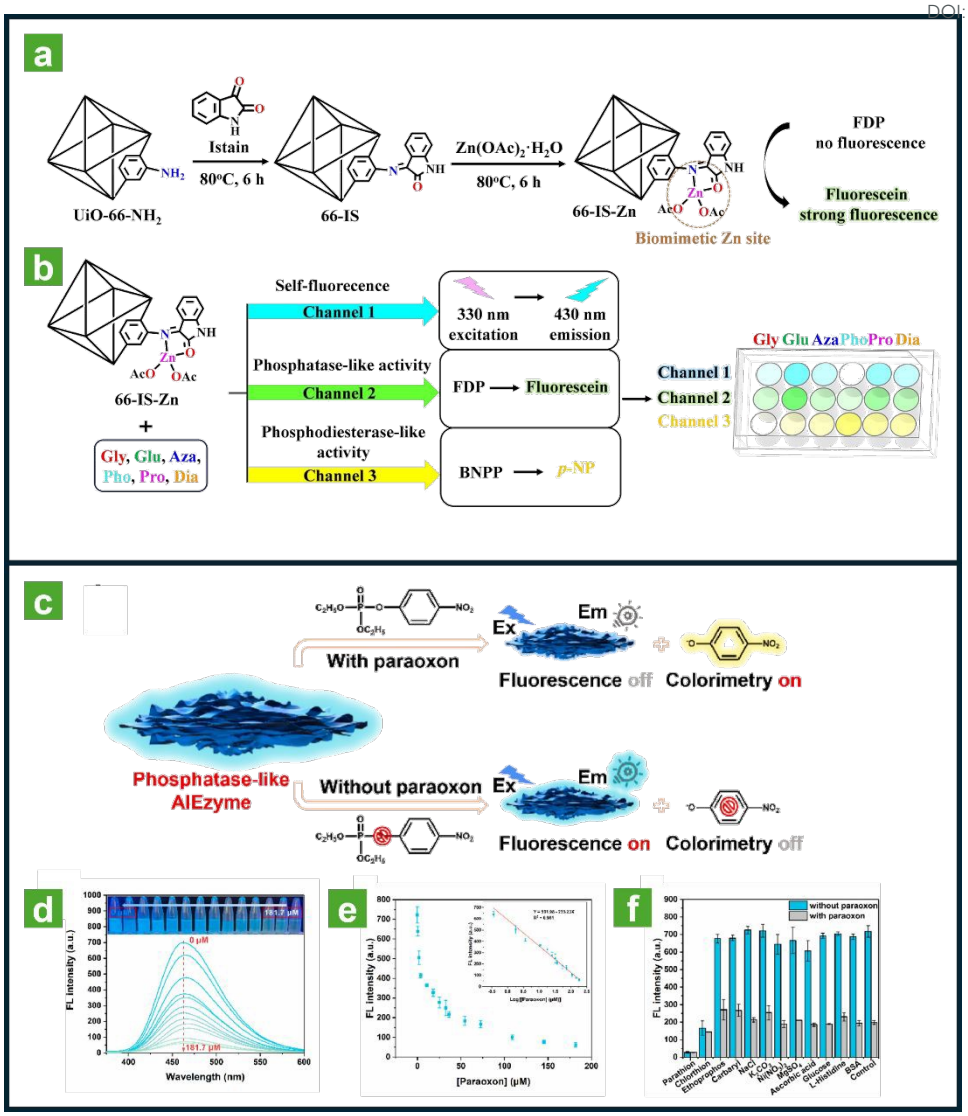


Fig. 5. Pesticide detection mechanism through modulation of intrinsic nanozyme fluorescence mechanism. (a) Diagram illustrating the synthesis of 66-IS-Zn via the covalent integration of biomimetic Zn centers into UiO-66-NH_2 and its catalytic role in FDP dephosphorylation. (b) Schematic representation of a 66-IS-Zn-based nanozyme sensor array designed for the differentiation of various OPs. Reproduced from reference[103] with permission from Elsevier, copyright 2025. (c) Detection mechanism of a dual-mode colorimetric and fluorometric platform for paraoxon sensing utilizing an AIEzyme. (d) Fluorescence emission profiles of the AIEzyme system in response to varying concentrations of paraoxon. (e) Calibration plot

View Article Online
DOI: 10.1039/D5TA09692H

showing the linear correlation between FL intensity and the logarithmic concentration of paraoxon. (g) Selectivity evaluation of the proposed fluorometric method against diverse interfering species. Reproduced from reference[64] with permission from Elsevier, copyright 2025.

4.3. Nanozymes for the electrochemical detection of pesticides

Electrochemical detection methods, owing to their outstanding advantages such as high sensitivity, rapid response time, cost-effectiveness, and potential for miniaturization, have established themselves as one of the most promising platforms for developing portable field-oriented pesticide monitoring systems.[124] In particular, the technology of integrating nanozymes onto electrode surfaces has opened new horizons in this field. By catalytically amplifying the electrochemical signals generated from the target pesticide or its byproducts, nanozymes dramatically enhance the sensor's analytical performance and play crucial role in lowering the detection limit to ultra-trace levels. Traditionally, pesticide residue analysis has relied on sophisticated instrumental techniques like GC-MS and LC-MS.[125] While these methods boast high accuracy, capable of analysis at sub-ppb (parts per billion) levels and simultaneous quantification of multiple components, they demand expensive equipment, skilled analysts, and complex, time-consuming sample preparation procedures. This has posed a critical limitation for on-site applications requiring immediate results, such as the rapid inspection of agricultural products before shipment or extensive environmental pollution monitoring. To bridge this gap, research on biosensors utilizing natural enzymes as biorecognition elements began in the 1960s.[126] In particular, sensors using AChE were widely employed for detecting organophosphate and carbamate pesticides[127]; however, the inherent

View Article Online
DOI: 10.1039/D5TA09692H

instability of the enzyme itself was the greatest obstacle to commercialization. Natural enzymes are highly sensitive to changes in the external environment, such as temperature, pH, and ionic strength, causing their tertiary structure to denature easily and lose activity. Furthermore, persistent issues were raised regarding high production costs, stemming from the complexity of extraction and purification from biological systems, and the difficulty in achieving sensor reproducibility due to large batch-to-batch variations in activity.[128, 129] It was at this convergence that 'nanozymes' artificial enzymes based on inorganic nanomaterials emerged as a powerful alternative, following the 2007 discovery that Fe_3O_4 nanoparticles exhibit peroxidase-like catalytic activity.[130] Nanozyme-based electrochemical sensors operate on the principle of converting a biochemical reaction into a measurable electrical signal, such as current, potential, or impedance. The nanozyme, immobilized on the working electrode, functions as the core recognition and signal amplification element.[131] Its enzyme-like catalytic activity towards a specific substrate which is either consumed or generated in the presence of the target pesticide forms the basis of detection.[132] This section begins by discussing the intrinsic advantages that nanozymes offer to electrochemical pesticide sensors. It then provides an in-depth analysis of the main detection mechanisms the enzyme inhibition-based and direct electrocatalytic methods and concludes with a thorough discussion on the latest design strategies to maximize sensor performance. Table 3 shows the comparative analysis of nanozyme-based electrochemical sensors for pesticide detection.

Table 3. Comparative analysis of nanozyme-based electrochemical sensors for pesticide detection

Nanozyme	Pesticides	Enzyme activity	LOD	Reaction time	Recovery rates	Ref.

View Article Online
DOI: 10.1039/D5TA09692H

Ni–SPNC	Atrazine	Peroxidase	2.3 fg/mL	30 min	94.9%-98.5 %	133
Fe_3O_4/Cu-MOF	Thiram	Laccase	36.1 pg/mL	1 min	98.42%-105.44%	134
FePrNS, NiPcNS	Paraoxon	Peroxidase	1.35 μg/mL	15 min	98.4 %	135
Pd@Pt NP	Atrazine, Acetochlor	Peroxidase	1 ng/mL	2 min	97.0%-109%	136
MB/COF@MnO_2, MCM	Dichlorvos	Oxidase	26 pg/mL	30 min	97.8 %-105 %	105
Au@MnO_{2-X}	Ethion, Omethoate, Diazinon, Chlorpyrifos methyl, Trichlorfon	Oxidase	39 pg/mL	10 min	95%-105%	137
Pt/Co_3O_4 nanoflowers	Thiram	Oxidase, Peroxidase, Catalase, Superoxide dismutase	15.63 ng/mL	15 min	95.33%-101.60%	77
NiCoFeS/rGO	Trichlorfon	Peroxidase	9.74fg/mL	20 min		138
MnNS	Paraoxon	Oxidase, Peroxidase	0.025 ng/mL	20 min		89
CeO_2 nanozyme	Methyl-paraoxon	Phosphatase	14.83 ng/mL	60 min	116.84% ± 1.42%	139
NiO nanoplatelets	Parathion	Oxidase	6.99 ng/mL		103 ± 2.13%	140
SA-Fe-NZ	Ethyl parathion, Dichlorvos, Omethoate	Peroxidase	1.03 fg/mL	3 min	99.14 %-104.27 %	141
COF-OMe@Valine-CeO_2	Methyl paraoxon	Phosphatase	2.72 ng/mL	5 min	97.46–111.10 %	142
ZrO_2@ZIF-90	Methyl parathion	Phosphohydrolase	0.14 pg/mL	4 min	89.25%-102.78%	143
CuO_x/GDYO	Chlorpyrifos	Peroxidase	0.20 ng/mL	20 min	96.62%–103.25 %	144

View Article Online
DOI: 10.1039/D5TA09692H

Cobalt-Doped Ti_3C_2 MXene	Paraoxon, Chlorpyrifos, Methidathion, Phoxim, Malathion, Profenofos, Carbaryl, Carbofuran	Peroxidase	0.02 ng/mL	30 min	97.4%-103.3%	[145]
Gold nanorods	Malathion, Methyl parathion, Chlorpyrifos, Parathion, Dichlorvos	Peroxidase	8.1 pg/mL	10 min	100&-110%	[146]
Au@Pt nanozyme	Parathion, Triazophos, Chlorpyrifos	Peroxidase	3.95 fg/mL	30 min	71.26%-117.47%	[147]

4.3.1. Strategic advantages of nanozyme-based electrochemical detection methods

The fusion of the unique catalytic properties of nanozymes with electrochemical transduction technology creates a significant synergistic effect in the field of pesticide detection. This goes beyond the mere sum of the two technologies, offering four key strategic advantages that can overcome the fundamental limitations of existing sensing paradigms. First is the intrinsic signal amplification and enhanced sensitivity. The sensitivity of an electrochemical sensor is ultimately determined by the magnitude of the Faradaic current generated at the electrode surface. Like natural enzymes, nanozymes follow Michaelis-Menten kinetics and can rapidly convert (turnover) numerous substrate molecules into products at a single catalytic site. This catalytic amplification mechanism enables a single molecule of the target analyte to trigger the generation or consumption of thousands, even tens of thousands, of electrochemically active molecules, thereby intrinsically amplifying the measurement signal.[137, 148] For example, a nanozyme with peroxidase-like activity can generate a massive current by oxidizing or reducing numerous redox mediators (e.g., TMB, ABTS), a process mediated by a single molecule of hydrogen peroxide (H_2O_2).[149] While the turnover number of a natural enzyme like horseradish peroxidase (HRP) reaches several hundred per second, well-designed single-atom nanozymes or certain metal oxide nanozymes exhibiting comparable or

View Article Online
DOI: 10.1039/D5TA09692H

sometimes even superior catalytic efficiency. In particular, the Km (Michaelis constant) value of a nanozyme indicates its affinity for a substrate, and some nanozymes have demonstrated lower Km values than natural enzymes, proving they can operate efficiently even at lower substrate concentrations.[150, 151] Because of this inherent amplification capability, nanozyme-based electrochemical sensors have the potential to detect ultra-trace levels of pesticides down to the femtomolar (fM) or even attomolar (aM) range levels difficult to achieve with traditional methods without the need for external, complex amplification systems (e.g., polymerase chain reaction, rolling circle amplification). Second is the maximization of interfacial electron transfer rates. An efficient electrochemical sensor relies on rapid and seamless electron transfer between the catalyst's active site and the electrode surface.[134] In the case of natural enzymes, the active site (e.g., a heme group) is often buried deep within a large protein structure (typically several to tens of nanometers in size), making direct electron transfer (DET) with the highly inefficient electrode. This is because the distance over which electrons can tunnel is typically limited to 1-2 nm. Consequently, diffusible mediators such as ferrocene derivatives or $[Fe(CN)6]^{3-/4-}$ are often required to facilitate electron transfer, which increases the sensor's complexity and response time.[28, 152] In contrast, nanozymes particularly nanozyme composites integrated with 2D conductive nanomaterials like graphene, carbon nanotubes (CNTs), and MXene create an ideal nano-environment at the electrode interface. These conductive nanomaterials act as "electron wires," facilitating the rapid transfer of electrons generated at the nanozyme's catalytic center to the electrode with minimal resistance.[27, 28] This, in turn, lowers the overpotential of the electrode reaction and reduces the charge transfer resistance (R_{ct}), ultimately leading to higher sensitivity at lower potentials and faster response times in the millisecond range.

View Article Online
DOI: 10.1039/D5TA09692H

Third is miniaturization, portability, and field applicability. Electrochemical analysis systems, which intrinsically consist of a potentiostat and electrodes, have a simpler configuration and are more easily miniaturized compared to other optical or mass spectrometry instruments. The introduction of nanozymes further enhances this practicality. Natural enzymes are typically irreversibly denatured at temperatures above 40-50°C and exhibit optimal activity only within a narrow pH range. Therefore, enzyme-based sensors must be operated under strict conditions and require frozen storage at temperatures below -20°C for long-term preservation. In contrast, metal oxide, noble metal, and carbon-based nanozymes, being intrinsically robust inorganic materials, maintain high stability at high temperatures (above 80°C), across a wide pH range (2-11), and even in organic solvents like acetonitrile and ethanol.[153] Thanks to this robustness, they can exhibit stable performance for several months at room temperature without requiring refrigeration, making them highly suitable for the development of field-oriented, disposable screen-printed electrode (SPE)-based sensors. By combining the excellent stability of nanozymes with the simplicity of electrochemical detection, it becomes possible to realize true point-of-care testing (POCT) devices that can be easily used by non-experts in locations such as agricultural fields, food processing facilities, and environmental water quality monitoring sites.[154-156] Fourth is cost-effectiveness and ease of mass production. The production of natural enzymes is expensive, requiring complex biological expression (e.g., in *E. coli*, yeast) and multi-step purification processes (e.g., chromatography). Furthermore, large batch-to-batch variations in activity make it difficult to ensure sensor reproducibility.[128, 129, 135] In contrast, nanozymes can be produced in large quantities and with high reproducibility from inexpensive precursors (e.g., $FeCl_3$, $HAuCl_4$, $Ce(NO_3)_3$) through well-established chemical synthesis methods such as hydrothermal synthesis, co-precipitation, and vapor deposition.[146, 147] For instance, Fe_3O_4 nanozymes can be easily

View Article Online
DOI: 10.1039/D5TA09692H

synthesized on a gram-scale or larger through a simple method of reducing iron salts in an aqueous solution, and their cost is merely a fraction as little as one-thousandth of that of purified HRP enzyme.[157, 158] This economy and productivity enable the mass production of disposable sensor strips, which can lower the per-unit cost. This significantly lowers the cost barrier for establishing extensive monitoring networks.[159] This serves as a particularly crucial advantage in budget-constrained applications, such as food safety management in developing countries or wide-area environmental surveillance.

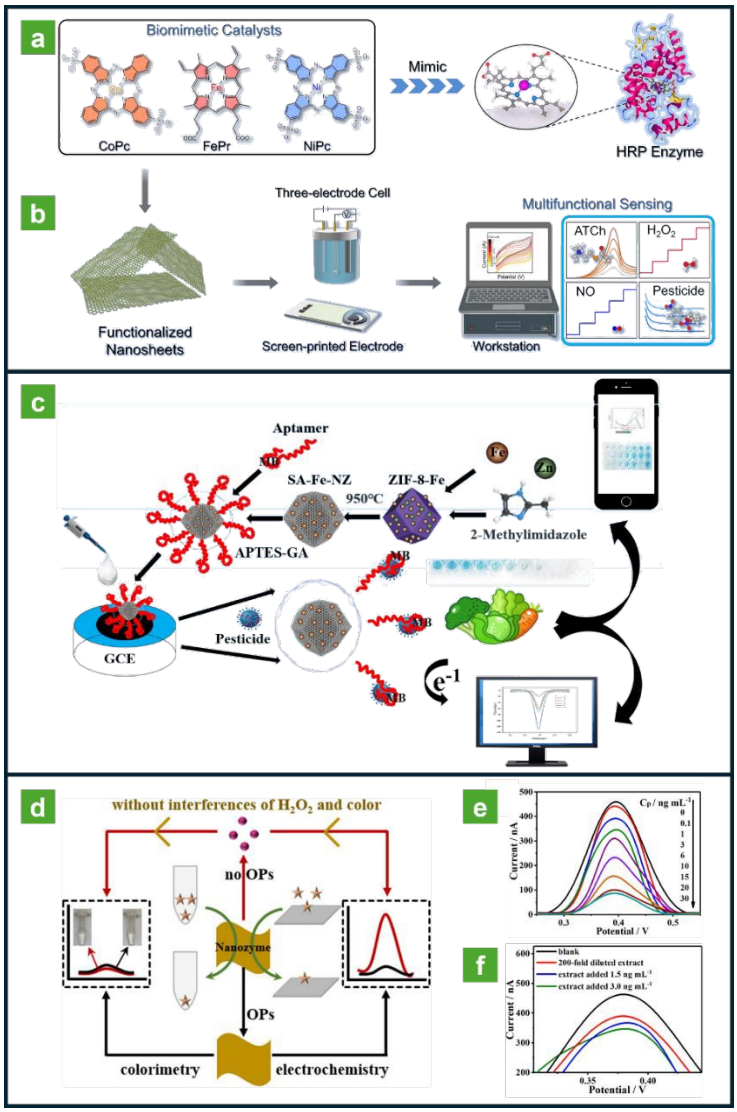
4.3.2. Classification of nanozyme-based electrochemical sensors for pesticide detection

The advantages of nanozyme-based electrochemical sensors stem from the flexibility to implement various detection mechanisms. This allows for the selection of an optimal sensor design strategy tailored to the specific type of pesticide, the required sensitivity and selectivity, and the application environment. Nanozyme-based electrochemical pesticide sensors primarily operate through catalytic activity modulation, direct electrocatalytic oxidation or reduction processes, or recognition-element mediated signal modulation, where interactions between pesticides and the nanozyme surface influence the electrochemical response of redox probes or electrode interfaces. In this section, nanozyme-based electrochemical pesticide sensors are classified into three core detection mechanisms, (i) signal-suppression sensors via catalytic activity inhibition, (ii) signal-generation sensors via direct electrocatalysis, and (iii) signal modulation sensors based on specific molecular recognition. This section aims to provide an in-depth analysis of the scientific principles, application examples, and technical limitations of each approach.[142, 160]

View Article Online
DOI: 10.1039/D5TA09692H

4.3.2.1. Signal-suppression sensors via catalytic activity inhibition

The signal-suppression approach is one of the most intuitive and widely studied methods for nanozyme-based sensors. The core principle of this mechanism involves the target analyte (the pesticide) inhibiting the activity of a catalyst-either a natural enzyme or a nanozyme within the system. This inhibition leads to a decrease in the electrochemical signal from its normal state, in proportion to the pesticide's concentration. This method is particularly effective for the detection of organophosphorus and carbamate pesticides, whose inhibitory effects on specific enzymes are well-established [138, 161].



View Article Online
DOI: 10.1039/D5TA09692H

Fig. 6. Pesticide detection through "Signal-suppression" via catalytic activity inhibition mechanism. (a) Schematic illustration of nanozymes functionalized with different biomimetic catalysts (CoPc, FePr, NiPc). (b) Electrochemical detection of ATCh, H_2O_2, and nitric oxide (NO) using functionalized nanozymes. Reproduced from reference[135] with permission from Elsevier, copyright 2023. (c) Schematic illustration of single-atom Fe nanozyme based dual-mode biosensor for multi-pesticide detection. Reproduced from reference[141] with permission from Elsevier, copyright 2024. (d) Schematic illustration of MnNS-based homogeneous electrochemical sensor for OP detection. (e) DPV spectra of the TMB-MnNS-ATCh-AChE platform in the presence of paraoxon at different concentrations. (f) DPV spectra of the TMB-MnNS-ATCh-AChE platform in the extracting solution spiked with paraoxon. Reproduced from reference[162] with permission from American Chemical Society, copyright 2021.

As an example of a 'signal-suppression' sensor that uses a catalytic activity inhibition mechanism, the paraoxon sensor developed by Niu et al. (2023) utilized a CoPcNS nanozyme combined with the natural enzyme AChE to detect the paraoxon. The CoPcNS nanozyme is a composite material created by combining sulfonated cobalt phthalocyanine (CoPc) with a base of graphene and the conducting polymer PEDOT (Fig. 6a). The sensor operates based on a cascade catalytic reaction between these two materials. First, the AChE enzyme hydrolyzes its substrate, acetylthiocholine, to produce thiocholine. Subsequently, the CoPcNS nanozyme efficiently oxidizes the generated thiocholine at the electrode, creating a strong baseline current signal. However, if paraoxon is present in the sample, it inhibits the activity of the AChE enzyme, which in turn prevents the production of thiocholine. As a result, the current signal generated by the nanozyme proportionally decreases (Fig. 6b). Through this principle, the

View Article Online
DOI: 10.1039/D5TA09692H

developed portable sensor achieved a low limit of detection for paraoxon of 1.1 μg/L and demonstrated high reliability and applicability in complex environments by showing results in real samples, such as tap water and cucumber, that were similar to those in standard solutions.[135]

In 2024, Wang et al introduced a dual-mode biosensor featuring a single-atom iron nanozyme (SA-Fe-NZ), synthesized via high-temperature pyrolysis of Fe-doped ZIF-8, for the multi-pesticide detection in vegetables (Fig. 6c). The platform utilizes the "toxic effect" of target-aptamer complexes, which bind to the surface of SA-Fe-NZ and inhibit its peroxidase-like activity, thereby preventing the catalytic oxidation of colorimetric substrates. Simultaneously, the electrochemical mode records changes in DPV signals as methylene blue (MB)-labeled aptamers undergo conformational changes upon binding to OPs, bringing the signal molecules closer to the electrode surface for current amplification. This broad-spectrum aptasensor achieved an exceptionally low LOD of 3.55 fM and a remarkably wide linear range from 10^{-13} to 10^{-2} M, offering high accuracy through the mutual validation of optical and electrochemical signals.[141] Wu's research group detected pesticides using 2D manganese dioxide nanosheets (MnNS) with dual oxidase- and peroxidase-like catalytic activities. This study presented an innovative mechanism that completely excludes H_2O_2 and instead directly utilizes dissolved oxygen as a coreactant. Fundamentally, the sensor relies on the AChE-catalyzed hydrolysis of acetylthiocholine (ATCh) to generate thiocholine (TCh). The generated TCh strongly inhibits the catalytic activity of the MnNS, thereby preventing the oxidation of the electrochemical probe TMB and maintaining a high DPV signal (Fig. 6d). However, when pesticides are present, AChE activity is inhibited, reducing TCh production. Consequently, the

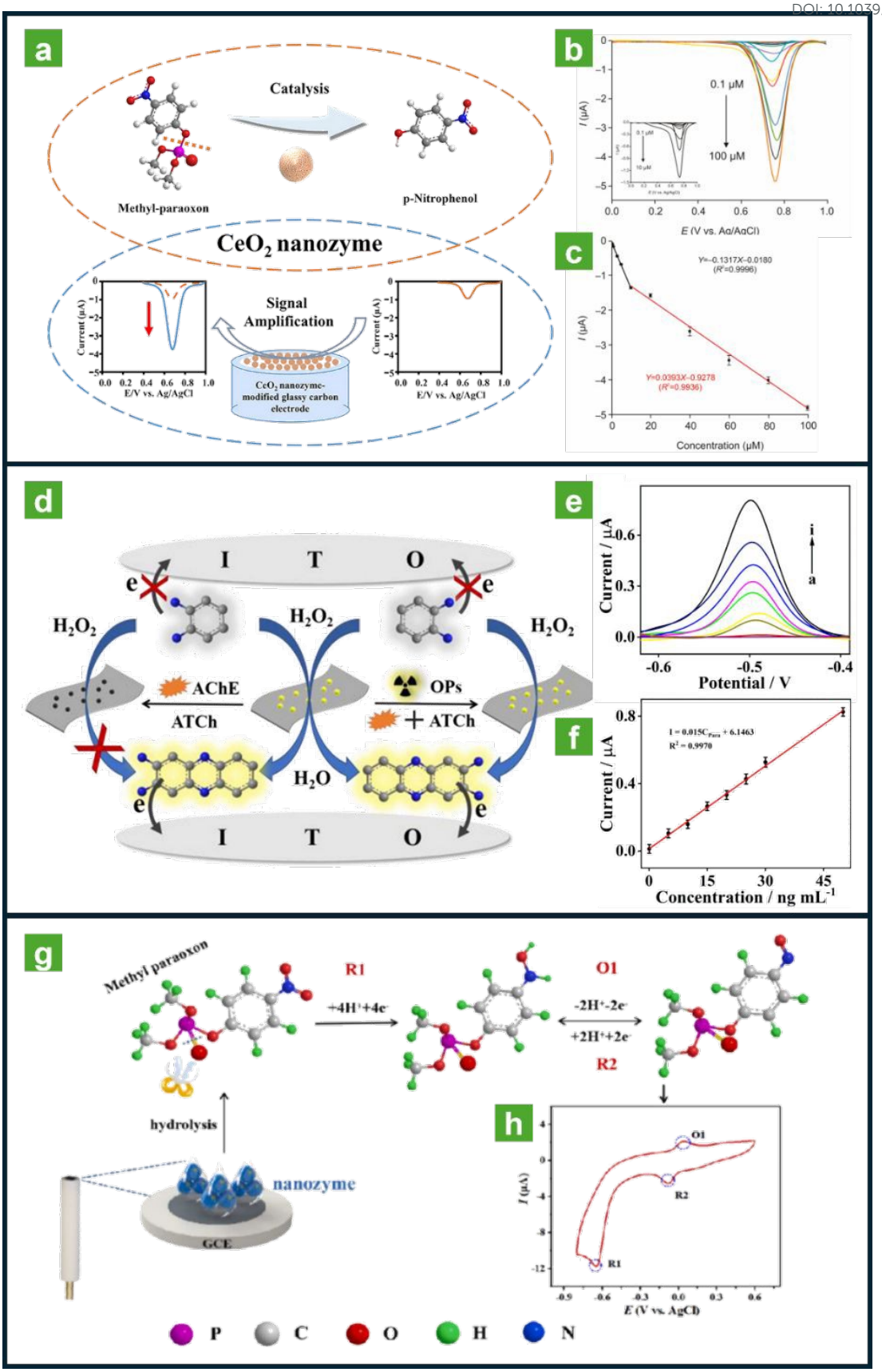
View Article Online
DOI: 10.1039/D5TA09692H

MnNS resumes the catalyzed oxidation of TMB, leading to a significantly declined DPV current. At this point, nanozymes maximize the sensor's performance through two key roles (Fig. 6e). Finally, when a pesticide inhibits AChE, no TCh is produced. Consequently, the MnNS resumes the catalyzed oxidation of TMB, leading to a significantly declined DPV current. This homogeneous electrochemical OP detection process based on the depressing AChE activity enables the highly sensitive detection of the pesticide. The sensor demonstrated high reliability, achieving a LOD of 0.025 ng/mL, excellent recoveries (99.72–102.41%), and high precision with relative standard deviations under 2.52% (Fig. 6f).[162]

4.3.2.2. Signal-generation sensors via direct electrocatalysis

As an alternative to inhibition-based methods, the 'signal-generation' approach is a versatile strategy for detecting various types of pesticides to which the enzyme inhibition mechanism cannot be applied. The core of this strategy involves using nanozymes as highly efficient electrocatalysts to directly oxidize or reduce the pesticide molecules themselves or their degradation byproducts, and then measuring the resulting Faradaic current. Consequently, the magnitude of the electrochemical signal increases in direct proportion to the concentration of the pesticide.

View Article Online
DOI: 10.1039/D5TA09692H



View Article Online
DOI: 10.1039/D5TA09692H

Fig. 7. Research trends in direct detection method. 'Signal-generation' sensors via direct electrocatalysis mechanism. (a) Schematic illustration of the electrochemical sensing mechanism for methyl-paraoxon detection utilized by CeO_2 nanozyme. (b) DPV responses of the CeO_2 nanozyme-modified electrode interface across a gradient of MP concentrations (0.1–100 μmol/L). (c) Quantitative calibration plot illustrating the linear dependence of the peak current on the corresponding concentrations of MP.[139] (d) Schematic illustration of the electrochemical sensing mechanism for paraoxon detection utilized by cobalt-doped Ti_3C_2 MXene nanozyme. (e) DPV responses of the common homogeneous electrochemical platform across a gradient of paraoxon concentrations (0 to 50 ng/mL). (f) Linear calibration plot correlating peak current intensity with the concentration of paraoxon. Error bars represent the standard deviation derived from three independent replicates. Reproduced from reference[145] with permission from American Chemical Society, copyright 2022. (g) Schematic illustration of the electrochemical sensing mechanism for MP detection utilized by COF-Ome@Valine-CeO_2 nanozyme. (h) CV spectrum of COF-OMe@Valine-CeO_2 in PBS (0.1 M pH 7.0) with addition of MP. Reproduced from reference[142] with permission from Elsevier, copyright 2024.

In 2021, the Sun research group reported a novel electrochemical method for detecting pesticides by using cerium oxide (CeO_2) as a nanozyme with the dual functions of catalytic reaction and signal amplification. This nanozyme possesses activity similar to organophosphorus hydrolase, which promotes the decomposition of MP and generates p-nitrophenol (Fig. 7a). Furthermore, by immobilizing the CeO_2 nanozyme on the electrode surface, it serves to amplify the electrochemical response of the p-nitrophenol product (Fig. 7b). This study used bifunctional nanozyme for pesticide detection. Operating on this principle,

View Article Online
DOI: 10.1039/D5TA09692H

the sensor provided a LOD of 0.06 μmol/L and successfully quantified methyl parathion in herb samples (Semen nelumbinis, Adenophora stricta, and Coix lacryma-jobi) with recoveries from 80.91% ± 4.86% to 116.84% ± 1.42% (mean ± SD, n=3) across various concentrations (Fig. 7c).[139] Organophosphate, phenolic, carbamate, and aniline-based pesticides possess electrochemically oxidizable functional groups within their molecules, such as phenolic hydroxyl groups, carbamate esters, or amine groups. In 2022, Yu's research group developed cobalt-doped 2D Ti_3C_2 MXene nanosheets (CMNSs) as a nanozyme with excellent peroxidase-like activity. This nanozyme can oxidize a specific substance, o-phenylenediamine (OPD), converting it into oxidized OPD (OPDOX), which generates a strong electrical signal (Fig. 7d). Interestingly, the nanozyme's activity is strongly inhibited by thiocholine, the product of the AChE enzyme reaction. Therefore, when the target pesticide first inhibits the activity of AChE, the production of thiocholine which would have interfered with the nanozyme is prevented. This allows the nanozyme to become active, resulting in a strong signal. In fact, the study observed that as the concentration of pesticides such as paraoxon, chlorpyrifos, and methidathion increased, the oxidation peak current of OPDOX grew proportionally stronger (Fig. 7e). In other words, this research successfully implemented a high-sensitivity sensor based on a 'turn-on' mechanism, where the presence of the pesticide triggers the generation of the signal molecule. The sensor exhibited both high sensitivity, with a LOD of 0.02 ng/mL, and high accuracy, demonstrated by recovery rates of 97.4% to 103.3% (Fig. 7f).[145] In 2024, Zhang et al. developed an ultrasensitive electrochemical sensor based on phosphatase-like COF-OMe@Valine-CeO2 nanozymes for the detection of organophosphorus pesticides, specifically methyl paraoxon (MP). In this nanozyme, the Ce(IV)/Ce(III) species serve as the active catalytic sites to polarize and hydrolyze the P=O bond in MP, leading to the formation of electroactive p-nitrophenol (p-NP). Furthermore, the biomimetic substrate-trapping pockets

View Article Online
DOI: 10.1039/D5TA09692H

of the porous COF-OMe exhibit excellent adsorption performance to capture MP, which synergistically promotes the hydrolysis process, while its covalent interface facilitates efficient charge transfer for electrochemical signal amplification (Fig. 7g). Based on this catalytic mechanism, the fabricated electrochemical sensor achieved a low limit of detection (LOD) of 0.011 μmol/L for MP (Fig. 7h). The practicability of the sensor was successfully validated in real samples (grapes and tap water), demonstrating satisfactory recoveries ranging from 97.46% to 111.10%.[142]

4.3.2.3. Signal modulation sensors based on specific molecular recognition

To overcome the limitations of the previous two mechanisms (e.g., reusability, selectivity), sophisticated sensor designs that combine catalytic behavior of nanozymes with highly specific molecular recognition elements, such as antibodies and aptamers, have recently been under active investigation. This approach is based on the principle where the specific binding event between a pesticide and a recognition element physically 'modulates' the nanozyme's activity or the properties of the electrode interface to generate a signal. Aptamers are single-stranded RNA or DNA sequences that bind to the specific molecules with high affinity. An aptamer specific to a pesticide is immobilized on the nanozyme surface. In absence of pesticide, the aptamer maintains a flexible structure, leaving the nanozyme's active site open or allowing a redox probe to easily access the electrode. When the pesticide binds, the aptamer folds into a three-dimensional structure (e.g., a hairpin, G-quadruplex), which can physically block the nanozyme's active site to turn the signal off, or conversely, expose a previously blocked active site to turn the electrochemical signal (Fig. 8a).[133]

View Article Online
DOI: 10.1039/D5TA09692H

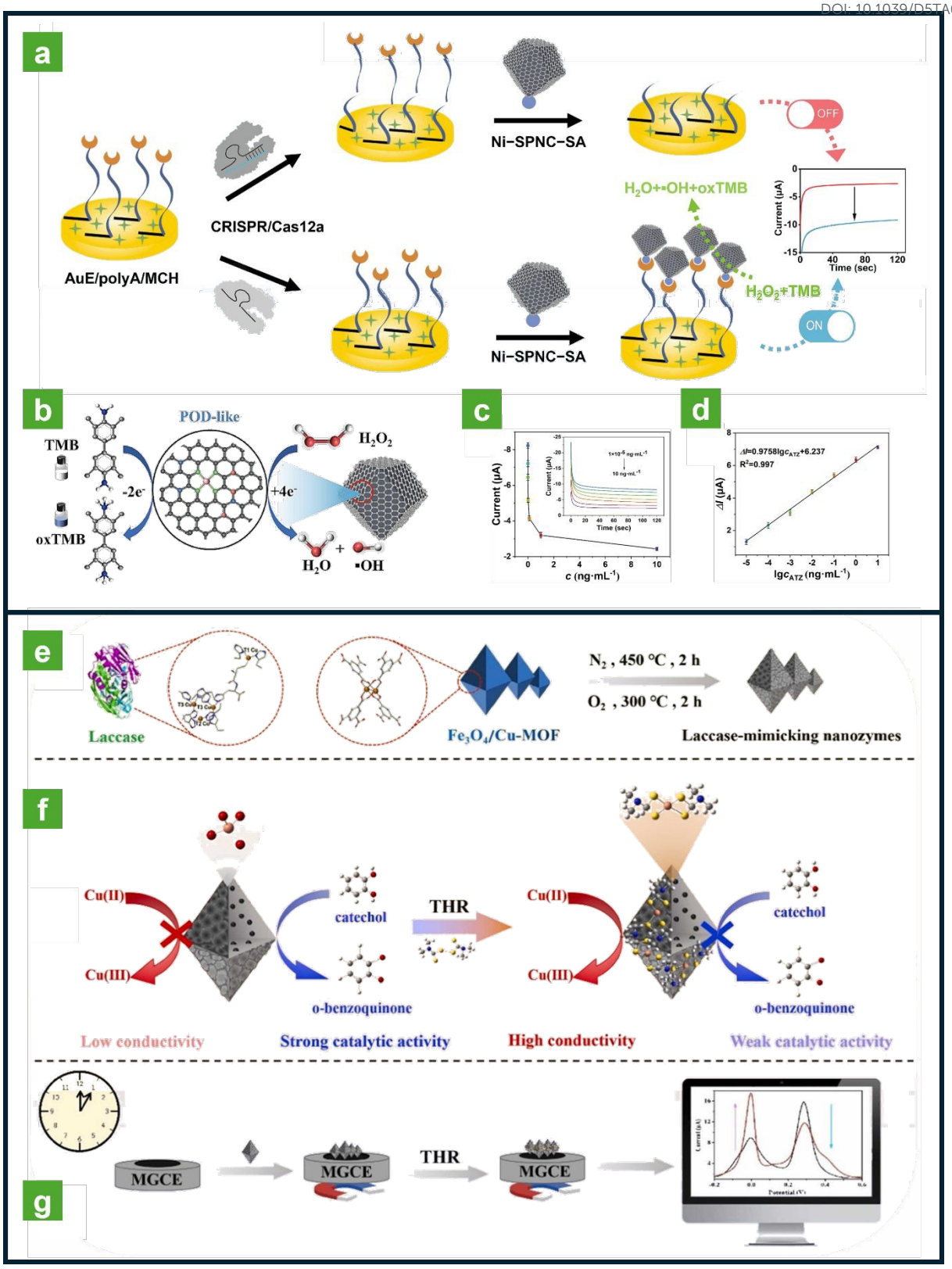


Fig. 8. Pesticide detection using signal modulation by specific molecular recognition

View Article Online
DOI: 10.1039/D5TA09692H

mechanism. (a) Schematic representation of the analytical workflow for atrazine (ATZ) monitoring using the proposed biosensor. (b) Evaluation of the peroxidase-mimicking catalytic performance of the synthesized SANs utilizing 20 mM TMB across various H_2O_2 concentrations. (c) Amperometric current-time (I - t) profiles of the electrochemical biosensor in response to varying ATZ levels ranging from 1×10^{-5} to 10 ng/L. (d) Linear calibration plot illustrating the relationship between the response current and the logarithmic concentration of ATZ. Error bars indicate the standard deviation of triplicate measurements (n=3). Reproduced from reference[133] with permission from Elsevier, copyright 2025 (e) Preparation of the bioinspired laccase-mimicking nanozyme for thiram detection. (f) Schematic of the ratiometric electrochemical sensing mechanism for thiram detection. (g) Label-free and rapid detection of thiram utilizing the magnetic glassy carbon electrode platform. Reproduced from reference[134] with permission from Elsevier, copyright 2024.

In the field of electrochemical biosensors, securing high selectivity for a target molecule is a critical challenge. Recently, in 2025, Han's research group reported a noteworthy study that solved this problem by utilizing an aptamer that specifically binds to ATZ, simultaneously achieving ultra-high sensitivity through multi-stage amplification. The core working principle of this sensor is as follows. In the presence of ATZ, the aptamer selectively binds with ATZ, which in turn 'turns on' the activity of a DNAzyme motor. The activated DNAzyme motor produces a large amount of trigger DNA, which then activates the CRISPR/Cas12a system to induce a cascade of cleavage reactions. This demonstrates a sophisticated design where a single selective recognition event by an aptamer triggers a massive signal amplification cascade. The final signal of this complex amplification process is handled by a newly developed Ni-SPNC

View Article Online
DOI: 10.1039/D5TA09692H

single-atom nanozyme (Fig. 8b). This nanozyme, through co-doping with P and S, possesses peroxidase-like activity superior to that of conventional materials. Finally, the amplification reaction prevents the nanozyme from binding to the electrode surface, enabling quantitative analysis through a mechanism where the signal decreases as the ATZ concentration increases. The effectiveness of this simple mechanism is highlighted by the sensor's performance, which includes a LOD of 2.3 fg/mL (Fig. 8c). Notably, a robust linear calibration plot was obtained by plotting the response current against the logarithmic concentration of ATZ (Fig. 8d). It also exhibited high accuracy, with recoveries of 94.9 - 98.5% and relative standard deviations of 1.18 - 5.26%.[133]

Building on the concept of signal modulation through molecular recognition, bioinspired ratiometric sensors have been designed to achieve even higher accuracy. In 2024, Geng et al. inspired by the multi-copper active centers ligated with amino acid residues in natural laccase, a magnetic MOF (Fe_3O_4/Cu-MOF) was synthesized as a precursor for electroactive nanozymes through a dual-step carbonization process (Fig. 8e). These nanozymes utilize their abundant Cu(II) active sites to catalyze the oxidation of catechol into electroactive o-quinone. When thiram is added, it forms a thiram-Cu(II) complex that specifically inhibits the laccase-mimicking activity of the nanozyme, resulting in a significantly lower oxidation current for catechol (Fig. 8f). Furthermore, the binding of thiram facilitates the internal electron transfer of the nanozymes, generating a concomitantly higher signal for Cu(II). This simultaneous decrease in the oxidation of catechol signal and increase in the Cu(II) signal enables a sensitive ratiometric electrochemical response, which effectively cancels out potential environmental interference. Finally, the intrinsic magnetic properties of the

View Article Online
DOI: 10.1039/D5TA09692H

nanocomposite allow for a label-less detection strategy using a magnetic glassy carbon electrode, enabling the entire analytical process to be completed in less than 5 min (Fig. 8g).[134]

4.4. Nanozymes for the SERS detection of pesticides

SERS spectroscopy has firmly established itself as one of the most powerful and sensitive molecular detection techniques in the field of analytical chemistry. This technique is based on the phenomenon where the scattering signal of molecules adsorbed onto the surface of specific metal nanostructures (primarily gold, silver, and copper) is dramatically amplified. SERS provides information about the unique vibrational modes of a molecule, generating a highly specific spectrum that acts like a "molecular fingerprint." The SERS technique can enhance these signals by factors of 10^6 to 10^{14}, theoretically achieving detection sensitivity at the single-molecule level. Due to this phenomenal sensitivity and high specificity, SERS has been recognized for its potential in diverse fields such as chemistry, materials science, biology, and environmental monitoring. It is considered an especially ideal tool for the analysis of pesticide residues, which requires the rapid and accurate identification of trace amounts of hazardous substances. Traditional SERS-based pesticide detection is broadly categorized into two approaches.[163, 164] The first is the "label-free" method, which directly measures the intrinsic signal of the pesticide molecules themselves. The second is the "label-based" method, which utilizes Raman reporter molecules that show distinct spectral changes upon interaction with a specific pesticide.[165] However, these approaches have faced several inherent limitations. In the case of the label-free method, there is a fundamental problem that most pesticide molecules have a low affinity for the surface of metal nanoparticles and a small Raman scattering cross-section, making it difficult to obtain a satisfactory SERS signal. While the label-based method

View Article Online
DOI: 10.1039/D5TA09692H

can improve sensitivity, it has disadvantages such as complex labeling processes, potential steric hindrance, and stability issues with the reporter molecules, all of which complicate the analytical procedure and increase costs.[166, 167]

The introduction of nanozymes is emerging as an innovative alternative to overcome the limitations of existing SERS techniques and to elevate analytical performance to a new level. Nanozymes are functional nanomaterials that mimic catalytic behavior of natural enzymes, possessing several advantages over them, such as superior stability, low production cost, and the potential for easy mass production.[168, 169] From an analytical chemistry perspective, the most intriguing feature of nanozymes is that some can simultaneously serve as both a plasmonic substrate for SERS signal enhancement and as an enzyme-like catalyst. For example, gold nanoparticles (AuNPs) and silver nanoparticles (AgNPs) are not only the most widely used plasmonic materials in SERS but also exhibit various catalytic functions, including peroxidase-like activity that oxidizes specific substrates in presence of H_2O_2.[170, 171] By integrating the dual functions of 'catalyst' and 'signal amplifier' within a SERS platform, nanozymes address the problems faced by conventional SERS sensors and enable new analytical strategies. The product generated through the nanozyme's catalytic reaction can act as a reporter molecule with a strong Raman signal. Since this product is generated in the immediate vicinity of the nanozyme surface, it is positioned within the electromagnetic field enhancement region where SERS signal amplification is maximized, thereby maximizing signal enhancement efficiency. Pesticides can act by either inhibiting or enhancing this catalytic activity of the nanozyme, which in turn leads to a variation in intensity of the finally measured SERS signal.[172, 173] Consequently, the introduction of nanozymes opens a new

View Article Online
DOI: 10.1039/D5TA09692H

avenue for detecting the presence of pesticide molecules indirectly, yet with very high sensitivity. This section aims to deeply discuss the latest research trends in the development of high-sensitivity, high-selectivity analytical platforms for pesticide detection by integrating SERS technology with the catalytic properties of nanozymes. Particularly, it will analyze the strategic advantages offered by nanozyme-based SERS detection methods and discuss the technological advancements in this field by classifying sensor systems according to their various operating principles. Table 4 shows the comparative analysis of nanozyme-based SERS sensors for pesticide detection.

Table 4. Comparative analysis of nanozyme-based SERS sensors for pesticide detection

Nanozyme	Pesticides	Enzyme activity	LOD	Reaction time	Recovery rates	Ref.
FeMOF@OCTB	Isocarbophos	Oxidoreductase	2.89 pg/mL		97.7%–104%	[174]
Co-Fe PBA@Ag	Glyphosate	Peroxidase	0.482 ng/mL	10 min	97.64%-104.87%	[175]
Pt@BSA–hapten	Triazophos	Peroxidase	1 ng/mL	1 min	80.5%-109.8%	[176]
Cu-O-Mo nanozyme	Pirimicarb	Peroxidase	100 ng/mL	10 min	108.1%	[164]
Fe_3O_4@Ag NPs	Thiram	Peroxidase	0.827 ng/mL	5 min	81.6%-108.2%	[163]
Sea-urchin-like Au@Pt	Chlorpyrifos	Oxidase	0.742 ng/mL	30 min	100.45%-101.43%	[177]

4.4.1. Strategic advantages of nanozyme-based SERS detection methods

The fusion of nanozymes and SERS technology transcends a simple combination of two techniques, creating a powerful synergistic effect that maximizes analytical performance. In

View Article Online
DOI: 10.1039/D5TA09692H

the field of pesticide detection, this synergy offers unique strategic advantages that overcome many limitations of conventional analytical methods. The core strengths of nanozyme-based SERS sensors can be summarized as (1) the synergistic integration of catalytic activity and signal amplification, (2) increased reproducibility of SERS signals and cost-effectiveness of the sensor, (3) flexible analytical design and multiplex detection capabilities, and (4) enhanced on-site applicability through simplified analytical procedures. Each of these benefits holds the potential to change the paradigm of pesticide monitoring technology, and they will be discussed in detail below. First, the synergistic integration of catalytic activity and signal amplification is the most fundamental and powerful advantage of the nanozyme-based SERS platform.[178] In traditional enzyme-linked SERS analysis, the enzyme that performs the catalytic reaction and the plasmonic substrate that amplifies the SERS signal exist as separate components. In this case, the Raman-active product generated by the enzymatic reaction must diffuse to the surface of the SERS substrate for the signal to be amplified. This diffusion process not only limits the reaction rate but also becomes a major cause of reduced signal amplification efficiency, as the product may reach a location outside the substrate's electromagnetic field enhancement region. However, the use of plasmonic nanozymes, such as AuNPs or AgNPs, fundamentally solves this problem. These nanomaterials are themselves excellent SERS substrates while simultaneously possessing enzyme-like activities, such as that of peroxidase. For instance, consider a system using a AuNPs with peroxidase-like activity (AuNP-nanozyme). In this system, the Raman-inactive substrate TMB is catalytically oxidized by the AuNP-nanozyme and converted into a blue-colored oxidized TMB (oxTMB), which produces a strong Raman signal. The key is that this conversion process occurs directly on the surface of the AuNP, the very source of the SERS signal enhancement. This means the catalytic active site where the Raman reporter is generated and the plasmonic surface where the SERS signal is amplified are

View Article Online
DOI: 10.1039/D5TA09692H

perfectly integrated within a single nanoparticle. This structure ensures that the generated oxTMB molecules are immediately positioned in the region of the most intense electromagnetic field enhancement, minimizing signal loss due to diffusion and maximizing both the reaction rate and signal amplification efficiency. While this specific TMB-oxidation system aptly illustrates the fundamental mechanism, its conceptual framework holds significant promise for pesticide monitoring. Theoretically, if this integrated platform were adapted so that a target pesticide selectively inhibits the catalytic activity of the AuNP-nanozyme, a corresponding reduction in oxTMB production would be expected. This inhibition could potentially translate into a quantifiable decrease in the SERS signal, offering an exceptionally sensitive and innovative strategy for future pesticide detection.[179, 180] As such, this physical and functional integration of catalyst and signal amplifier serves as the core mechanism for dramatically improving the sensitivity and responsiveness of the analytical system. Second, nanozymes provide high signal reproducibility and cost-effectiveness, which are essential for the practical application of SERS-based sensors. The intensity of a SERS signal is extremely sensitive to the chemical state of the plasmonic substrate's surface and the rate of the catalytic reaction. When using natural enzymes, even minor environmental changes, such as in temperature or pH, can easily denature the enzyme, leading to a decrease or irregularity in its catalytic activity. This, in turn, results in fluctuations in the generation rate of the Raman analysis, which is a primary cause of severely compromised reproducibility in the final measured SERS signals. In contrast, nanozymes, being robust inorganic nanomaterials, maintain stable catalytic activity even under harsh conditions, thereby ensuring consistent and reliable SERS signals in a variety of real sample environments. This stability not only allows for the long-term storage of the sensors but also provides a foundation for the mass production of uniform-quality SERS substrates with minimal batch-to-batch variation, thus enhancing the

View Article Online
DOI: 10.1039/D5TA09692H

reliability of analytical results. From a cost-effectiveness perspective, the low production cost of nanozymes enables the development of affordable, disposable SERS sensors.[181] In practical field analysis, the use of disposable sensors is crucial to prevent cross-contamination between samples. Substrates that rely on expensive natural enzymes or require complex fabrication processes struggle to meet this demand. However, nanozymes are ideal for disposable platforms due to their potential for low-cost mass production.[182] This provides the economic feasibility for SERS technology to expand beyond the confines of expensive laboratory equipment into user-friendly, on-site diagnostic tools. Ultimately, the stability and economy of nanozymes are key factors in achieving consistent SERS signals and practical analysis costs, playing a decisive role in accelerating the technology's commercialization.

Third, the nanozyme-based SERS platform demonstrates outstanding potential in its flexibility of analytical design and multiplexing capabilities. The catalytic and plasmonic properties of a nanozyme can be optimized by precisely controlling the nanoparticle's size, shape, composition, and surface chemistry.[183] For example, anisotropic nanostructures with sharp vertices or edges, such as gold nanostars or silver nanocubes, can generate much stronger electromagnetic fields compared to spherical nanoparticles, thereby maximizing the SERS enhancement effect. At the same time, these structural variations also influence the nanozyme's catalytic activity, making it possible to simultaneously tune both properties to fit specific analytical objectives. Furthermore, the surface of a nanozyme can be easily functionalized with various molecular recognition elements through methods like thiol (-SH) bonding or electrostatic interactions. By immobilizing elements with high affinity and specificity for a particular pesticide such as aptamers, antibodies, or molecularly imprinted polymers (MIPs)

View Article Online
DOI: 10.1039/D5TA09692H

onto the nanozyme-SERS substrate, the target pesticide can be selectively captured, dramatically improving the selectivity of the analysis.[184, 185] This design flexibility extends to multiplex detection. A key feature of SERS spectra is that they exhibit very narrow peaks at unique positions for each molecule. Therefore, by using several types of reporter molecules that produce distinct Raman signals, it is possible to simultaneously quantify multiple types of pesticides in a single measurement. For instance, one could design multiple nanozyme systems, each regulated by a different pesticide and engineered to generate a unique Raman analysis. By integrating these systems onto a single substrate, the concentrations of various pesticides can be determined at once by analyzing the peak intensity of each analysis in the measured SERS spectrum. This multiplexing capability saves time and money, reduces sample consumption, and presents a highly effective solution for analyzing real agricultural and environmental samples where multiple types of pesticides are often co-mingled.[163]

Fourth, the integration of nanozymes and SERS significantly simplifies the analytical procedure, greatly enhancing its applicability for rapid POCT. As mentioned earlier, because the catalyst and the signal transducer are integrated into a single nanoparticle, the sensor fabrication process is simplified, and the number of analytical steps is reduced. Many nanozyme-based SERS analysis systems can be implemented in a "mix-and-read" format, where the sample and reagents are mixed, allowed to react for a certain period, and then the SERS signal is measured. This is a tremendous advantage compared to traditional methods like chromatography-mass spectrometry (LC-MS/GC-MS), which require complex sample pretreatment, separation, and purification steps.[177] The analysis time is reduced from hours to minutes, and measurements can be performed without expensive, bulky equipment or highly

View Article Online
DOI: 10.1039/D5TA09692H

skilled analysts. This simplification has true potential when combined with a portable Raman spectrometer. Recent technological advancements have led to the development of high-performance, palm-sized portable Raman devices, paving the way for the direct use of nanozyme-SERS platforms wherever they are needed at agricultural production sites, distribution centers, food processing plants, and water quality management sites.[186] This enables real-time, on-site screening for pesticide contamination, which maximizes the efficiency of food safety management systems and contributes to proactively preventing threats to public health through rapid responses to contamination incidents. As such, the procedural simplicity and on-site applicability offered by nanozyme-based SERS technology will be a key driving force in shifting the paradigm of pesticide safety management from centralized laboratory analysis to decentralized, on-site diagnostics.

4.4.2. Classification of nanozyme-based SERS sensors for pesticide detection

Although nanozyme-based SERS sensors for pesticide detection can be designed in a wide variety of forms, their fundamental operating principles can be broadly classified into two key mechanisms based on how the target pesticide affects the nanozyme's catalytic activity. The first is the 'direct modulation of nanozyme activity' mechanism, in which the pesticide molecule itself directly inhibits or enhances catalytic activity of nanozyme. The second is the 'indirect modulation via recognition element' mechanism, where the pesticide first binds to a separate recognition element, such as an aptamer or a MIP, and this binding event then indirectly controls the active state of the nanozyme. This classification provides an important framework for understanding the operating principles of these sensors.

View Article Online
DOI: 10.1039/D5TA09692H

4.4.2.1. Direct modulation of nanozyme activity

The first mechanism, 'direct modulation' is based on the principle that the pesticide molecule alters the intrinsic catalytic efficiency of the nanozyme, either by binding directly to its active site or by scavenging key intermediates like reactive oxygen species (ROS) that are generated during the catalytic process. This approach is an intuitive strategy that utilizes the unique chemical properties or reactivity of the pesticide as a core element for signal generation. This mechanism can be further divided into two subtypes including inhibition and enhancement.

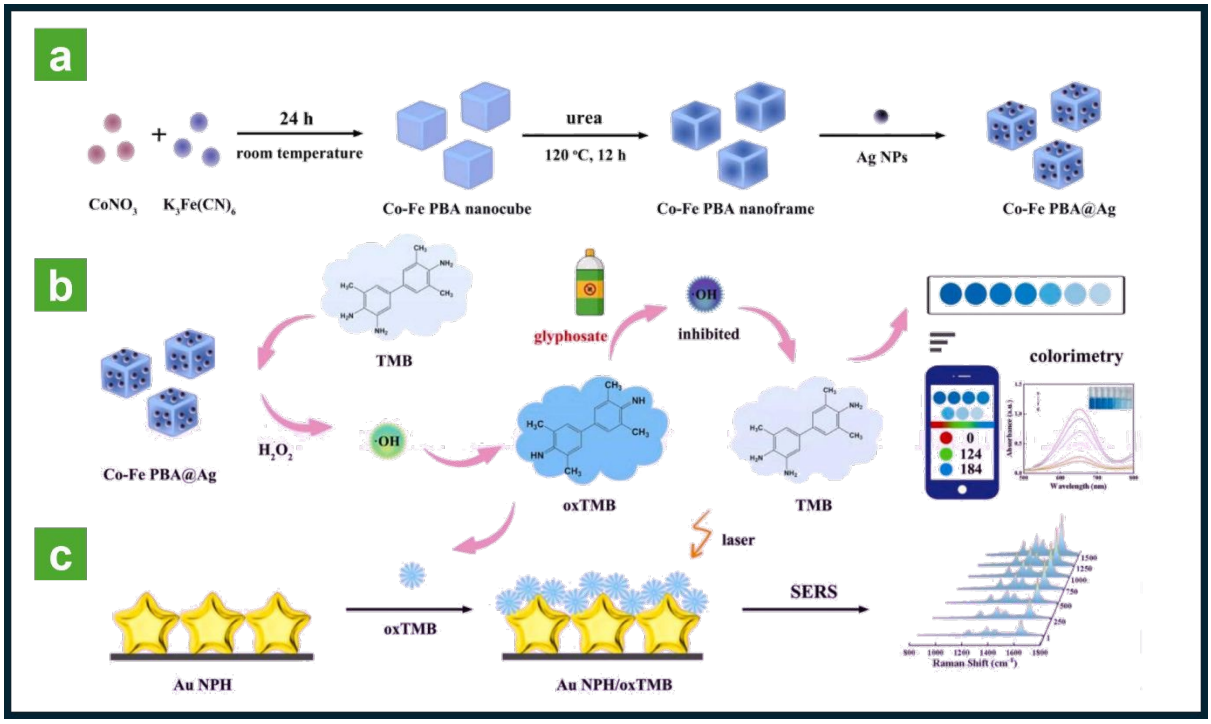


Fig. 9. Pesticide detection through direct modulation of nanozyme activity mechanism. (a) Schematic for the synthesis of Co-Fe PBA@Ag for glyphosate sensing. (b) Sensing mechanism of glyphosate based on Co-Fe PBA@Ag (c) SERS-based detection of glyphosate using Co-Fe PBA@Ag. Reproduced from reference[175] with permission from Elsevier, copyright 2025.

View Article Online
DOI: 10.1039/D5TA09692H

Activity inhibition is the most common direct modulation method, implementing a 'turn-off' sensor where the SERS signal decreases as the pesticide interferes with the nanozyme's catalytic function. A prime example of direct inhibition was reported in 2025 by He's research team for a glyphosate detection sensor. The Co-Fe PBA@Ag nanozyme was prepared through a multi-stage strategy starting with the synthesis of Co-Fe PBA nanocubes. To increase the specific surface area and active sites, these nanocubes were subjected to urea etching under hydrothermal conditions at 100℃ for 12 h, resulting in the formation of concave nanoframes with a sunken surface. Finally, AgNPs were assembled onto the polyethylenimine (PEI)-modified nanoframes to yield the bimetallic Co-Fe PBA@Ag composite, which exhibits significantly enhanced peroxidase-like catalytic activity due to the synergistic effects between the metals (Fig. 9a). The Co-Fe PBA@Ag nanozyme used in this sensor decomposes H_2O_2 to generate hydroxyl radicals (•OH), a powerful oxidizing agent, which in turn oxidize TMB. Glyphosate, rather than binding to the nanozyme itself, has the ability to effectively scavenge the hydroxyl radicals, which are the key intermediates of the catalytic reaction. In other words, glyphosate reacts with and deactivates the hydroxyl radicals before TMB can, thus hindering TMB's oxidation (Fig. 9b).[175] For ultrasensitive quantification, gold polyhedra (Au NPH) were employed as the SERS-enhancing substrate. The irregular morphology of the Au NPH facilitates the generation of numerous SERS signal. This also induces a 'turn-off' response where the SERS signal decreases as the glyphosate concentration increases (Fig. 9c). An extremely low LOD of 2.85 nM was achieved using the nanozyme SERS sensor designed with this mechanism. The sensor's reliability in complex matrices was confirmed with high recovery rates for honey (97.64–104.87%), potato (97.87–104.86%), and tea (98.46–104.75%). As shown, the direct inhibition method is highly effective as it directly leverages specific chemical properties of pesticides, such as the affinity of certain functional groups (e.g., thiols, amines)

View Article Online
DOI: 10.1039/D5TA09692H

for the nanozyme's active site or the pesticide's radical-scavenging ability.

4.4.2.2. Indirect modulation via recognition element

The second mechanism, 'indirect modulation via a molecular recognition element' is a strategy where the nanozyme's own catalytic activity is kept constant, while a third-party molecular recognition element (e.g., aptamer, MIP) that specifically binds to the pesticide is introduced to control the overall signal output. In this approach, the nanozyme focuses on its role as a signal-generating reporter, and the sensor's selectivity depends entirely on the performance of the molecular recognition element. The binding event between the pesticide and the recognition element induces physical and structural changes in the system, and these changes affect the nanozyme's catalytic reaction environment, ultimately leading to a change in the final SERS signal. The aptasensor for isocarbophos (IPS) detection, developed by Li's research team in 2022, is a typical example of this indirect modulation method. In this system, a DNA aptamer that specifically binds to IPS is first physically adsorbed onto the surface of a FeMOF@OCTB nanozyme. In this adsorbed state, the nanozyme's active sites are covered, and the catalytic reaction is inhibited (Fig. 10a). However, if IPS is present in the sample, the aptamer binds to IPS with a much stronger affinity than to the nanozyme surface, causing it to detach. As the aptamer is released, the nanozyme's active sites are re-exposed, allowing the nanozyme to recover its original catalytic activity. This restoration of catalytic performance is manifested as a concentration-dependent colorimetric response, which can be quantitatively monitored through UV-vis absorption spectra (Fig. 10b). Furthermore, the recovered activity promotes the reduction of Ag^+ ions into Ag nanoparticles. The resulting AgNPs act as a SERS substrate, generating a strong signal. In other words, the pesticide acts as an inducer that

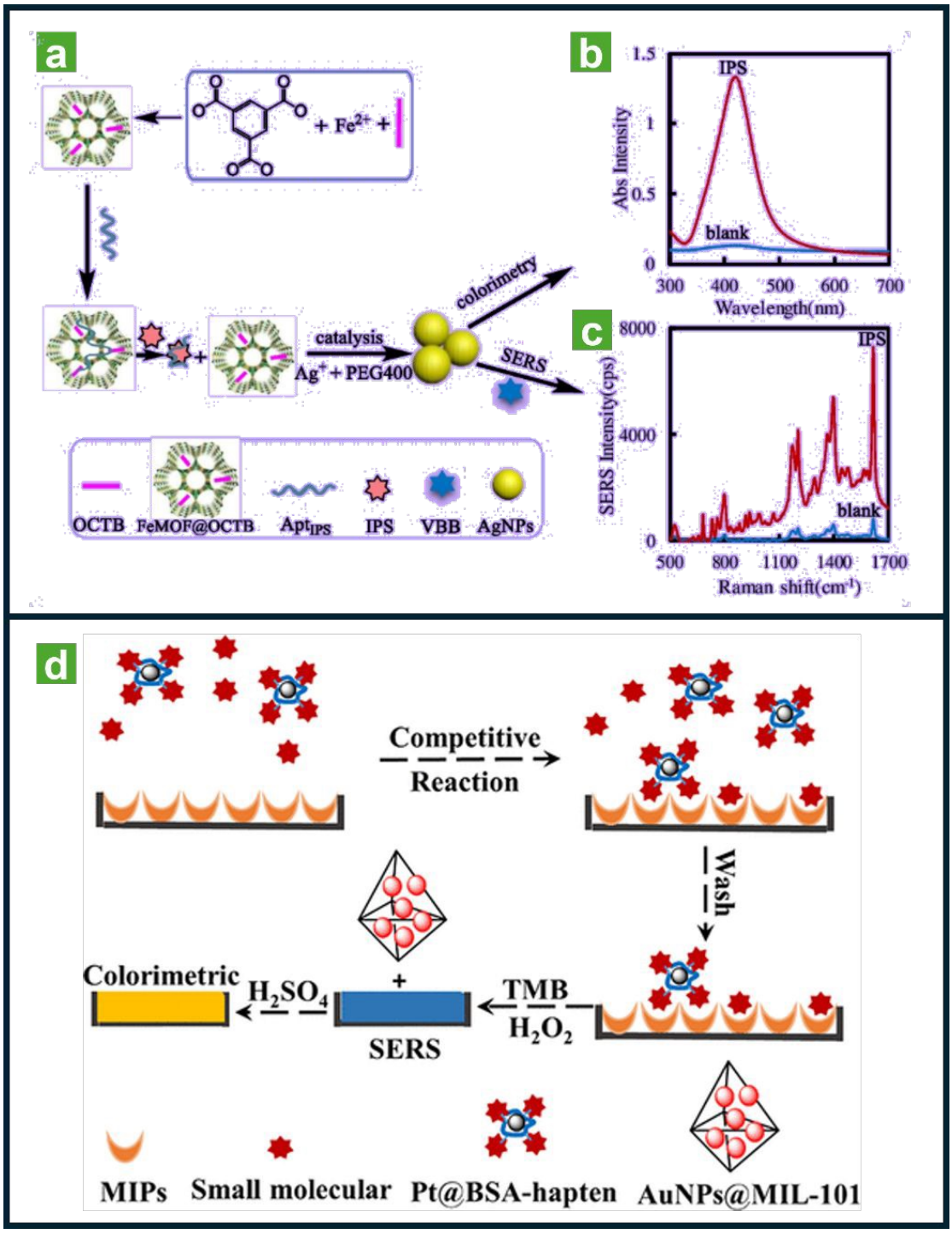
View Article Online
DOI: 10.1039/D5TA09692H

releases the aptamer that was inhibiting the catalytic activity, thereby restarting the suppressed catalytic reaction and generating a 'turn-on' signal (Fig. 10c).[174]

The sensor for triazophos detection, developed by Yan's research team in 2019, is another example of indirect modulation that uses the principle of competitive immunoassay. In this system, a MIP with recognition sites for triazophos is first immobilized on a 96-well plate. Separately, a 'nanozyme-labeled competitor' (Pt@BSA-hapten) is prepared by conjugating a nanozyme (PtNPs) to a structural analog (hapten) of triazophos. During analysis, the sample containing triazophos and a fixed amount of the nanozyme-labeled competitor are added simultaneously to the MIP-coated wells. At this point, the triazophos from the sample and the nanozyme-labeled competitor compete for the limited number of MIP binding sites. If the concentration of triazophos in the sample is high, it will occupy most of the MIP binding sites, leaving the nanozyme-labeled competitor unable to bind and to be removed during the washing step. Therefore, the final measured SERS signal is very weak. Conversely, if there is no or a low concentration of triazophos in the sample, most of the nanozyme-labeled competitor will bind to the MIP, generating a strong SERS signal. This results in a typical 'turn-off' competitive analysis curve, where the signal decreases as the pesticide concentration increases (Fig. 10d).[176] Nanozyme-based SERS sensors can be clearly distinguished by whether the pesticide directly influences the nanozyme's activity or indirectly affects it through a separate recognition element. The direct modulation approach allows for the construction of relatively simple systems by leveraging the chemical properties of the pesticide. In contrast, the indirect modulation approach offers the advantage of securing excellent selectivity and versatility by utilizing highly specific recognition elements such as aptamers or MIPs. An understanding of

View Article Online
DOI: 10.1039/D5TA09692H

these mechanisms will serve as a crucial theoretical foundation for designing and developing high-performance SERS sensors optimized for specific pesticides and analytical environments in the future.



View Article Online
DOI: 10.1039/D5TA09692H

Fig. 10. Pesticide detection using indirect modulation via recognition element mechanism. (a) FeMOF@OCTB catalytic amplification mechanism for isocarbophos detection. (b) UV-vis absorption spectra showcasing the concentration-dependent colorimetric response toward isocarbophos. (c) SERS signal recovery resulting from the target-induced release of Fe-MOF@OCTB from the aptamer-nanozyme complex. Reproduced from reference[174] with permission from Springer Nature, copyright 2022. (d) Pt@BSA-Hapten catalytic amplification mechanism for triazophos detection. Reproduced from reference[176] with permission from American Chemical Society, copyright 2019.

A comparative analysis of the reported nanozyme-based pesticide sensors reveals several common design principles that influence analytical behaviors of colorimetric, fluorescence, electrochemical, and SERS sensing platforms. Structural engineering of nanozymes such as heterostructure formation, surface functionalization, defect-rich nanomaterials and increased catalytic activity, enhances active site exposure, and facilitates transfer of electron processes, thereby improving response kinetics and sensitivity. In optical sensing systems, including colorimetric and fluorescence methods, catalytic activity modulation of nanozymes, particularly the inhibition or alteration of peroxidase-like activity by pesticides, represents the most employed detection mechanism. Electrochemical sensors frequently exploit nanozyme-assisted electrocatalysis or catalytic inhibition to modulate redox signals at electrode interfaces, while SERS-based systems typically rely on nanozyme-assisted catalytic generation of Raman-active species or plasmonic signal amplification mediated by analyte surface interactions.

View Article Online
DOI: 10.1039/D5TA09692H

Despite the substantial progress reported in these sensing strategies, several trade-offs remain between sensitivity, operational robustness, and material cost. Noble metal-based nanozymes (e.g., gold, platinum, palladium) exhibit exceptional catalytic activity, yet their high cost and limited availability raise concerns regarding material criticality and large-scale deployment. Conversely, carbon-based nanozymes, transition metal oxides, and metal organic framework-derived systems, provide more cost-effective, improved chemical stability, and better scalability. Sometimes they exhibit comparatively lower catalytic efficiency. Another important limitation observed across many studies is the limited validation of sensor performance in complex real-world matrices. While numerous reports demonstrate excellent analytical sensitivity under controlled laboratory conditions, systematic testing in real agricultural products, food matrices, and environmental water samples is still relatively limited, leaving potential interference effects insufficiently addressed. Hence, future development of nanozyme-based pesticide sensors should focus on improving sensor robustness, enhancing selectivity, and performing comprehensive real-sample validation to facilitate reliable deployment in the practical monitoring applications.

Nanozymes have revolutionized pesticide analysis by providing robust alternatives to natural enzymes, showcasing significant potential across colorimetric, fluorescent, electrochemical, and SERS-based sensing platforms. An in-depth exploration of the discussed four key detection modalities was provided, by systematically analyzing their strategic advantages, operating principles, and interaction mechanisms. While nanozyme technology enables the development of ultra-sensitive and highly selective analytical methods, the choice of a specific platform depends heavily on specific analytical requirements, such as the desired sensitivity, sample

View Article Online
DOI: 10.1039/D5TA09692H

matrix complexity, and the availability of instrumentation at the point of need. Each modality offers unique benefits while facing distinct technical hurdles; for instance, colorimetric sensors excel in rapid, equipment-free screening, whereas SERS and electrochemical platforms are favored for ultra-trace quantification and high precision. Table 5 outlines best-use scenarios, key limitations, failure modes, and mitigation strategies for each modality. Through this multifaceted approach, we aim to provide a comprehensive outlook on the limitless potential of innovative nanozymes as next-generation, sensing technologies for safeguarding future food security and environmental safety.

Table 5. Decision matrix for selecting nanozyme-based sensing modalities for pesticide detection.

Modality	Preferred Scenarios	Key Limitations	Potential Failure Modes	Mitigation Strategies
Colorimetric	Rapid on-site screening, naked-eye detection, low-cost disposable kits	Lower sensitivity compared to optical/electrical methods	High background color from real samples	Use of smartphone-based RGB analysis or ratiometric color shifts
Fluorescence	High-sensitivity requirements, real-time imaging	Susceptibility to photobleaching and background fluorescence	Signal quenching by non-target matrix components (Matrix effect)	Implementation of dual-emission ratiometric probes or AIE-active nanozymes
Electrochemical	High-sensitivity requirements, portability (POCT)	Electrode fouling due to bio-adsorption in complex samples	Loss of signal due to non-specific adsorption (Biofouling)	Surface modification with anti-fouling layers
SERS	Ultra-trace detection, molecular fingerprinting, multiplexing	Signal reproducibility issues and complex substrate fabrication	Inconsistent signals due to "hotspot" non-uniformity	Design of uniform 3D superstructures or use of internal standards

Key design rules and practical recommendations for nanozyme-based pesticide sensors

View Article Online
DOI: 10.1039/D5TA09692H

Based on collective analysis of recent studies, key design rules and practical recommendations can be proposed for assistance in designing high-performance nanozyme-based pesticide sensing systems across colorimetric, electrochemical, fluorescence, and SERS platforms.[187, 188] These include rational selection of catalytic substrates and signal reporters, engineering nanozyme catalytic activity and nanostructure, enhancing selectivity through surface functionalization, minimizing the matrix interference, signal amplification strategies, improving stability and reproducibility, balancing sensitivity, cost, and scalability, and validation in real-world matrices.[14, 84, 189]

5. Challenges and future perspectives

5.1. Colorimetric detection

While nanozyme-based colorimetric sensors have made remarkable progress, several significant challenges must be addressed to achieve widespread commercialization and on-site application. First is the challenge of ensuring selectivity and reproducibility in complex real samples. Real samples such as fruits, vegetables, and soil contain numerous organic substances, salts, and proteins in addition to the target pesticide, which can cause a 'matrix effect' that interferes with the nanozyme's activity.[23, 46, 190] Although many studies discussed herein have demonstrated feasibility by applying their sensors to real variant samples with excellent recovery rates of over 90%, validation across a broader and more diverse range of matrices is needed.[48-51, 54, 57, 59, 61, 64, 65, 67, 68, 70, 73, 75-77] To overcome this, research into developing robust nanozymes that are less affected by the sample matrix, or combining them with simple yet effective pretreatment techniques, is essential. Second, a more fundamental understanding of the catalytic mechanisms is still needed. Despite the reporting of numerous high-efficiency

View Article Online
DOI: 10.1039/D5TA09692H

nanozymes, identification of exact structure of active sites and the atomic-level elucidation of how they interact with pesticide molecules to modulate activity are still in their early stages.[191, 192] For instance, the study on the Pt-Np-C nanozyme identified that a specific nitrogen configuration (Pyridinic N) around the platinum active site plays a crucial role in pesticide recognition, but in-depth studies at this level are still lacking.[63] Efforts to clarify reaction mechanisms through computational science and in-situ characterization techniques will provide the foundation for designing 'tailor-made nanozymes' in a more rational and sophisticated manner, moving beyond empirical development. Future research on nanozyme-based colorimetric sensors is expected to advance in several promising directions. The development of intelligent and multifunctional systems will accelerate.[26] This includes the creation of highly integrated materials where a single nanozyme can simultaneously detect multiple pesticides or perform both degradation and detection of pesticides. Furthermore, research on 'smart' nanozymes, such as the Pt/Co_3O_4 nanoflowers that engineered by *Sun et al.* in 2022, whose function can be modulated by external stimuli like pH, will expand, allowing for stimuli-responsive sensing platforms.[77] These advancements will be further amplified through integration with portable smart devices. The use of smartphone cameras and dedicated applications for quantitative analysis of colorimetric signals, already actively pursued in many cases, could evolve into extensive data management systems by integrating with Internet of Things (IoT) technology to transmit measurement data to the cloud in real-time and create pesticide contamination maps.[51, 66, 70] In conclusion, nanozyme-based colorimetric sensors, through continuous and interdisciplinary research to overcome current technical challenges, hold the potential to firmly establish themselves as a universal and reliable on-site analytical technology for protecting the future of food and environmental safety, ultimately contributing to public health and sustainable agriculture.

View Article Online
DOI: 10.1039/D5TA09692H

5.2. Fluorescence detection

While nanozyme-based fluorescence detection methods show outstanding potential in the field of pesticide analysis, there are still technical challenges and limitations that must be overcome for their transition to real-world applications and commercialization. At the same time, this field is rapidly advancing, with new research directions and innovative approaches continuously being proposed, so its future prospects can be considered very promising. One of the most significant challenges is the complex matrix effect and the influence of interfering substances. These substances can inhibit the catalytic activity of nanozymes or interfere with the fluorescent signal. Therefore, ensuring selectivity and specificity is crucial. Structurally similar pesticides or cross-reactive interfering substances can lead to the false positive or false negative results. This is especially true in complex biological samples, where the concentration of interfering substances (μM-mM) can be millions of times higher than the target analyte concentration (fM-nM), requiring an extremely high selectivity on the order of 10^9:1. Although solutions utilizing aptamers or molecular imprinting technology are being proposed, improvements in the efficiency of the aptamer screening process and precise control of nanozyme-aptamer interactions are needed. Furthermore, direct detection methods using only nanozymes are fundamentally limited in selectivity due to the lack of recognition units, making the development of sensor arrays or pattern recognition-based approaches essential.[193, 194] Issues of reliability and reproducibility are key hurdles to commercialization. Single-mode detection systems have inherent reliability limitations, making them vulnerable to false signals or instrumental fluctuations. To address this, dual-mode (fluorescent-colorimetric) or multi-mode detection systems are being developed, which can significantly enhance reliability through intrinsic self-verification and self-correction functions. However, reproducibility

View Article Online
DOI: 10.1039/D5TA09692H

issues stemming from batch-to-batch variability in nanozyme synthesis, changes in activity depending on storage conditions, and the influence of the measurement environment still need to be resolved.[195, 196] Despite the clear limitations of nanozyme-based fluorescence detection technology, the potential for growth in this field is limitless, with several innovative research directions indicating future breakthroughs. Particularly, designing sensing materials with high selectivity will be a key focus. To solve the current problems of matrix effects and non-specific interference, future nanozymes will be combined with advanced molecular recognition systems such as molecular imprinting technology or aptamers. This is analogous to designing "customized pockets" on the nanozyme surface to precisely capture specific pesticide molecules. Furthermore, 'computer-aided nanozyme engineering' will be realized by utilizing artificial intelligence and computational science to predict and design active sites that perfectly match the 3D structure and charge distribution of a specific pesticide. This will grant the ultimate selectivity, enabling a reaction only with the target molecule even in complex samples.

5.3. Electrochemical detection

Although nanozyme-based electrochemical pesticide sensors have shown remarkable achievements, significant challenges remain in translating laboratory-level success into reliable, commercially viable products for field use. Real samples, such as agricultural products, soil, and river water, contain numerous interfering substances like proteins, fats, humic acids, and inorganic salts. These substances can adsorb onto the electrode surface, inhibiting the nanozyme's activity (biofouling) or causing non-specific signals, which severely compromises the sensor's accuracy and reproducibility.[197-199] Therefore, it is essential to develop effective sample preparation techniques or to integrate anti-fouling surface modification technologies

View Article Online
DOI: 10.1039/D5TA09692H

(e.g., coating with polyethylene glycol or zwitterionic polymers).[200-203] Despite the experimentally proven high catalytic activity of many nanozymes, the exact structure of their active sites and their catalytic reaction pathways often remain unclear. Clarifying the structure-activity relationship by combining theoretical studies, such as density functional theory calculations, with real-time spectroscopic analysis is a prerequisite for the rational design of next-generation nanozymes with tailored activity and selectivity for specific pesticides.[148, 204, 205] Standardization and quality control also make challenges. The shape, size, and surface chemistry of nanozymes are highly sensitive to synthesis conditions, which leads to batch-to-batch variations in catalytic activity. To ensure sensor reliability, the establishment of standardized synthesis and quality control protocols for precisely controlling and analyzing nanozyme properties is urgently needed.[140] Despite these challenges, the future is advancing substantially. Artificial intelligence and machine learning can be utilized to analyze vast experimental datasets to predict optimal nanozyme compositions and structures, and to screen for new candidate materials. This will enable a shift from traditional 'trial-and-error' research methods to efficient, data-driven nanozyme development.[206, 207] Furthermore, integration with microfluidics technology will enable the creation of 'Lab-on-a-Chip' systems that automate the entire process from sample injection, mixing, and reaction to detection on a single chip. This will minimize sample consumption, reduce analysis time, and decrease user error, thereby maximizing the accuracy and convenience of on-site analysis.[208, 209] Ultimately, multiplexed analysis platforms will be developed by integrating multiple nanozyme sensors, each selective for a different pesticide, onto a single array. This will allow for the simultaneous quantitative analysis of various pesticides in a single measurement. When these technologies are combined with wireless communication and the IoT, it will become possible to build distributed environmental monitoring networks that can monitor pesticide contamination in real-time over

View Article Online
DOI: 10.1039/D5TA09692H

wide areas and transmit the data to a central server.[210]

5.4. SERS detection

Combination of nanozymes and SERS technology has led to remarkable advancements in the field of pesticide detection by providing excellent sensitivity and convenience, several significant challenges still need to be addressed before this technology can move beyond laboratory-level proof-of-concept to become a commercialized, on-site analytical tool. These challenges include ensuring the reliability and reproducibility of quantitative analysis and overcoming the matrix effects of complex real-world samples. However, these challenges also serve as signposts for future research directions in this field. It is anticipated that future research will move towards overcoming current limitations and maximizing the technology's practical value through the rational design of nanozymes, the development of intelligent hybrid materials, and the construction of multi-modal analysis systems. One of the most pressing challenges currently facing by the nanozyme-based SERS sensors is ensuring the reliability and reproducibility of quantitative analysis. The SERS signal is extremely sensitive to the distance between and arrangement of nanoparticles, that is, the distribution of 'hotspots'.[211] The simple method of drying a nanozyme solution onto a substrate can lead to a non-uniform distribution of nanoparticles due to the 'coffee-ring effect' that occurs as the solvent evaporates. This can result in SERS signals that vary by more than an order of magnitude depending on the measurement spot, which is a critical drawback that makes accurate quantitative analysis nearly impossible.[212] Furthermore, minor batch-to-batch variations in the size or shape of nanozymes during synthesis lead to non-uniformity in their catalytic activity and plasmonic properties, which is another factor that undermines the reproducibility of the sensor's performance.[213]

View Article Online
DOI: 10.1039/D5TA09692H

Future research aimed at solving these challenges will unfold more sophisticated and intelligent directions. First, the rational design of nanozymes will become a core research theme. Moving beyond the conventional trial-and-error approach, research will actively utilize computer simulations like DFT and machine learning to predict the correlation between the structure, composition, and catalytic-plasmonic properties of nanomaterials. This will enable the design of 'customized nanozymes' with active sites and surface characteristics optimized for specific pesticides.[214, 215] Particularly, nanozymes with active centers clearly defined at the atomic level, such as platinum single-atom nanozymes, will provide crucial model systems for fundamentally understanding and controlling catalytic mechanisms. Second, efforts to overcome current limitations through the development of intelligent hybrid materials will accelerate. For example, immobilizing nanozymes within porous materials like MOFs or COFs can prevent nanozyme aggregation, thereby increasing stability and providing a uniform reaction environment. Furthermore, by controlling the pore size or chemical properties of MOFs, they can be designed to act as a 'molecular sieve,' selectively allowing only pesticide molecules of a certain size to pass through. They can even be endowed with the ability to pre-concentrate target pesticides by attaching molecular recognition elements like aptamers or antibodies to the MOF surface.[216] Such hybrid systems can offer innovative solutions that minimize matrix effects while simultaneously enhancing both selectivity and sensitivity. Nanozyme-based SERS technology holds immense potential in the field of pesticide detection. While current technical hurdles such as reproducibility and matrix effects are evident, these limitations will gradually be overcome through future-oriented research, including rational design via computational science, the development of intelligent hybrid materials, and integration with smart devices. When these efforts come to realization, nanozyme-SERS technology will establish itself as a powerful and reliable technology, keeping food and

View Article Online
DOI: 10.1039/D5TA09692H

environment safe.

5.5. Concrete recommendations for standardization and practical application

To bridge the gap between laboratory-level proof-of-concept and commercial on-site applications, it is imperative to move beyond general challenges and establish strict, concrete guidelines for the development of nanozyme-based pesticide sensors. Because the shape, size, and surface chemistry of nanozymes are highly sensitive to synthesis conditions, leading to batch-to-batch variations, future studies must adhere to minimum reporting standards. Researchers should explicitly detail precursor concentrations, precise thermal protocols, and kinetic parameters. Furthermore, to ensure commercial viability, it is highly recommended to systematically evaluate and report the inter-batch relative standard deviation (RSD) for catalytic activity. Ideally, this RSD should be maintained below 5–10%, which strongly aligns with the universally accepted analytical guidelines and the high precision recently demonstrated by state-of-the-art nanozyme sensors (e.g., RSDs of <2.52%, 1.18–5.26%, and <6.17%).[133, 162, 217] Achieving such low batch-to-batch variation across at least three independently synthesized batches is essential for practical commercialization.

While nanozymes are fundamentally more robust than natural enzymes, empirical long-term stability data is often missing in current literature. Concrete storage and shelf-life testing must become standard practice. Proposed sensors should be subjected to systematic aging tests to evaluating catalytic retention at both room temperature and 4 °C over a minimum period of 3 to 6 months. This specific timeframe is not arbitrary. Instead, it represents the

View Article Online
DOI: 10.1039/D5TA09692H

minimum viable shelf-life required to accommodate the manufacturing-to-distribution supply chain and covers a full seasonal cycle of agricultural pesticide monitoring. Furthermore, it empirically validates the intrinsic advantage of inorganic nanozymes, which are known to maintain stable catalytic performance for several months without rigorous refrigeration requirements. Achieving an activity retention of >90% over this period should serve as a baseline metric for practical, field-ready commercial sensors. In addition, biofouling and non-specific adsorption on sensor surfaces drastically reduce reproducibility when analyzing complex real-world samples.

Finally, matrix effects from real samples, such as agricultural runoffs or crude fruit extracts, cannot be ignored during practical implementation. To mitigate these interferences, simple external calibration is often insufficient. The routine adoption of standard addition methods or ratiometric sensing approaches should be highly encouraged to self-calibrate and eliminate background environmental fluctuations. Furthermore, any proposed sensor must undergo rigorous validation across at least three structurally different sample matrices. The analytical accuracy must be quantified by spiking standard pesticides and calculating recovery rates, which should strictly fall within the universally acceptable analytical range of 80% to 120%, alongside intra-assay RSDs tightly controlled below 10%.

6. Conclusions

- Chemical pesticides are essential for maintaining agricultural production and guaranteeing global food security by efficiently managing pest infestations in crops and storage facilities. Continual dependence on pesticides poses significant problems. Insufficient safety protocols, including farmers' limited understanding of safety labels

View Article Online
DOI: 10.1039/D5TA09692H

and the absence of appropriate protective gear, intensify health and environmental hazards. The detrimental consequences of pesticide application are profoundly affecting human health both physically and neurologically while also hurting non-target organisms, soil quality, groundwater, and local climatic conditions. Acknowledging the essential role of pesticides in agricultural production, similar to the function of medicine in disease management, underscores the significance of proper application procedures. It is vital to implement targeted applications for the successful management of pests while protecting food crops. Systematic surveillance of pesticide residues prior to their transportation and consumption is essential to mitigate risks, including the refusal of contaminated shipments in global trade.

- Advancements in nanotechnology have led to considerable interest in nanomaterials owing to their remarkable physical, mechanical, optical, and chemical capabilities. Nanozymes are a category of nanomaterials demonstrating enzyme-like functions. Nanozymes have garnered significant attention since their inception in 2004 and have emerged as a key research focus in the domain of artificial enzymes. Nanozymes mitigate several drawbacks of natural enzymes, including complex manufacturing and purification processes, inadequate stability, and reduced recycling effectiveness. Various nanozyme-based techniques have been designed for identifying levels of OPs in biosensor and food security applications. Nanozyme-based biosensors provide considerable advantages in OPs detection, with their analytical performance primarily demonstrated by operational simplicity, high sensitivity, excellent selectivity, and reliability.

View Article Online
DOI: 10.1039/D5TA09692H

- The distinctive properties of nanozymes, such as enzyme-like catalytic activity, structural adaptability, operating durability, and versatility, facilitate their incorporation into various detection methodologies, ranging from colorimetric and fluorescent sensors that provide rapid visual or optical outputs, to electrochemical platforms characterized by excellent sensitivity and real-time quantification, and SERS systems offering highly sensitive molecular identification. Across these detection methodologies, nanozymes will function through various mechanisms, such as inhibition of intrinsic enzyme activity, direct catalytic interaction with the molecules of pesticide, amplification of signals through molecular specific recognition, and alteration of electron transfer pathways, enabling versatile design strategies for the detection of various classes of pesticides. The growing demand for improved detection systems has generated significant interest in innovative sensing technologies. The latest advancements in materials chemistry and nanozymes emphasize the importance of potential sensors.

- In this review, we provided a critical overview on nanozymes for OPs detection, encompassing their material compositions, strategies for activity enhancement, output signals, and detection methodologies. Explicitly provided a detailed summary on the progress and perspectives of nanozyme-based SERS sensors, electrochemical sensors, fluorescence sensors, and colorimetric sensors for high-sensitivity sensing of pesticides. By presenting the recent trends and advances of nanozymes for the detection of pesticides, this review aims to provide a scientific reference for the utilization of innovative nanozymes in pesticides detection, facilitating their practical utilization in convenient and rapid analysis.

View Article Online
DOI: 10.1039/D5TA09692H

Acknowledgements

The authors acknowledge financial support from the Brain Pool Program (RS-2024-00447409) and the Basic Science Research Program (RS-2026-25483852) through the National Research Foundation of Korea (NRF), funded by the Ministry of Science, ICT, and Future Planning. This research was supported by a grant (25192MFDS001) from Ministry of Food and Drug Safety in 2025.

View Article Online
DOI: 10.1039/D5TA09692H

References

1. Z. Chen, R. Feng, Q. Zhou, X. Zhang, Y. Fan, D. Fang, R. Zheng, W. Zhang, Z. Lu, J. Chen, Q.-W. Zhang, C. Jiang, P. Li, H. Yu and G. Li, Biomaterials and biosensing technologies in the detection and removal of pesticide residues: Current trends and future prospects, Coordination Chemistry Reviews, 2026, 547, 217110. https://doi.org/10.1016/j.ccr.2025.217110.
2. S. Naveen Prasad, V. Bansal and R. Ramanathan, Detection of pesticides using nanozymes: Trends, challenges and outlook, TrAC Trends in Analytical Chemistry, 2021, 144, 116429. https://doi.org/10.1016/j.trac.2021.116429.
3. F. Zhao, L. Wang, M. Li, M. Wang, G. Liu and J. Ping, Nanozyme-based biosensor for organophosphorus pesticide monitoring: Functional design, biosensing strategy, and detection application, TrAC Trends in Analytical Chemistry, 2023, 165, 117152. https://doi.org/10.1016/j.trac.2023.117152.
4. X. Li, M. Liu, W. Sun, X. Meng, K. Du, K. H. Row and Y. Chang, Visual Strategies of Molecularly Imprinted Sensors for Rapid Warning of Pesticide Residues: Smartphone-Based Visual Detection, TrAC Trends in Analytical Chemistry, 2025, https://doi.org/https://doi.org/10.1016/j.trac.2025.118472118472. https://doi.org/10.1016/j.trac.2025.118472.
5. R. Umapathi, B. Park, S. Sonwal, G. M. Rani, Y. Cho and Y. S. Huh, Advances in optical-sensing strategies for the on-site detection of pesticides in agricultural foods, Trends in Food Science & Technology, 2022, 119, 69–89. https://doi.org/10.1016/j.tifs.2021.11.018.
6. R. Umapathi, S. Sonwal, M. J. Lee, G. Mohana Rani, E.-S. Lee, T.-J. Jeon, S.-M. Kang, M.-H. Oh and Y. S. Huh, Colorimetric based on-site sensing strategies for the rapid detection of pesticides in agricultural foods: New horizons, perspectives, and challenges, Coordination Chemistry Reviews, 2021, 446, 214061. https://doi.org/10.1016/j.ccr.2021.214061.
7. R. Umapathi, S. M. Ghoreishian, S. Sonwal, G. M. Rani and Y. S. Huh, Portable electrochemical sensing methodologies for on-site detection of pesticide residues in fruits and vegetables, Coordination Chemistry Reviews, 2022, 453, 214305. https://doi.org/10.1016/j.ccr.2021.214305.
8. R. Umapathi, C. Venkateswara Raju, S. Majid Ghoreishian, G. Mohana Rani, K. Kumar, M.-H. Oh, J. Pil Park and Y. Suk Huh, Recent advances in the use of graphitic carbon nitride-based composites for the electrochemical detection of

View Article Online
DOI: 10.1039/D5TA09692H

hazardous contaminants, Coordination Chemistry Reviews, 2022, 470, 214708. https://doi.org/10.1016/j.ccr.2022.214708.

9. R. Umapathi, G. M. Rani, E. Kim, S.-Y. Park, Y. Cho and Y. S. Huh, Sowing kernels for food safety: Importance of rapid on-site detction of pesticide residues in agricultural foods, Food Frontiers, 2022, 3, 666–676. https://doi.org/10.1002/fft2.166.

10. R. Umapathi, S. M. Ghoreishian, G. M. Rani, Y. Cho and Y. S. Huh, Review—Emerging Trends in the Development of Electrochemical Devices for the On-Site Detection of Food Contaminants, ECS Sensors Plus, 2022, 1, 044601. 10.1149/2754-2726/ac9d4a.

11. T. G. Ambaye, A. Hassani, M. Vaccari, A. Franzetti, S. Prasad, F. Formicola, A. Rosatelli, M. Z. u. Rehman, G. Mohanakrishna, S. V. Ganachari, T. M. Aminabhavi and S. Rtimi, Emerging technologies for the removal of pesticides from contaminated soils and their reuse in agriculture, Chemosphere, 2024, 362, 142433. https://doi.org/10.1016/j.chemosphere.2024.142433.

12. S. Tanveer, N. Ilyas, N. Akhtar, N. Akhtar, N. Bostan, Z. Hasnain, A. Niaz, G. Zengin, A. Gafur and B. N. Fitriatin, Unlocking the interaction of organophosphorus pesticide residues with ecosystem: Toxicity and bioremediation, Environmental Research, 2024, 249, 118291. https://doi.org/10.1016/j.envres.2024.118291.

13. A. Jha, D. Pathania, Sonu, B. Damathia, P. Raizada, S. Rustagi, P. Singh, G. M. Rani and V. Chaudhary, Panorama of biogenic nano-fertilizers: A road to sustainable agriculture, Environmental Research, 2023, 235, 116456. https://doi.org/10.1016/j.envres.2023.116456.

14. X. Lin, Y. Huang, J. Zou, G. Zhu, L. Pang and Y. Chen, Recent advances in nanozymes for organophosphorus pesticide detection in food, Chem Commun (Camb), 2025, 61, 14510–14530. 10.1039/d5cc03464g.

15. C. Venkateswara Raju, C. Hwan Cho, G. Mohana Rani, V. Manju, R. Umapathi, Y. Suk Huh and J. Pil Park, Emerging insights into the use of carbon-based nanomaterials for the electrochemical detection of heavy metal ions, Coordination Chemistry Reviews, 2023, 476, 214920. https://doi.org/10.1016/j.ccr.2022.214920.

16. R. Umapathi, C. V. Raju, M. Safarkhani, J. Haribabu, H. U. Lee, G. M. Rani and Y. S. Huh, Versatility of MXene based materials for the electrochemical detection of phenolic contaminants, Coordination Chemistry Reviews, 2025, 525, 216305. https://doi.org/10.1016/j.ccr.2024.216305.

View Article Online
DOI: 10.1039/D5TA09692H

17. A. T. E. Vilian, R. Umapathi, S.-K. Hwang, Y. S. Huh and Y.-K. Han, Pd–Cu nanospheres supported on Mo2C for the electrochemical sensing of nitrites, Journal of Hazardous Materials, 2021, 408, 124914. https://doi.org/10.1016/j.jhazmat.2020.124914.
18. A. T. Ezhil Vilian, R. Umapathi, S.-K. Hwang, M. J. Lee, Y. S. Huh and Y.-K. Han, Simple synthesis of a clew-like tungsten carbide nanocomposite decorated with gold nanoparticles for the ultrasensitive detection of tert-butylhydroquinone, Food Chemistry, 2021, 348, 128936. https://doi.org/10.1016/j.foodchem.2020.128936.
19. B. Kariyanna, S. Senthil-Nathan, P. Vasantha-Srinivasan, B. V. Subba Reddy, A. Krishnaiah, N. H. Meenakshi, Y. S. Han, S. Karthi, A. K. Chakravarthy and K. B. Park, Comprehensive insights into pesticide residue dynamics: unraveling impact and management, Chemical and Biological Technologies in Agriculture, 2024, 11, 182. 10.1186/s40538-024-00708-4.
20. R. Singh, A. Sharma, O. Bainik, B. Navyatha, C. Santhosh, E. Banoth, R. Balaji, N. Chandrasekar, S. Kumar and H. K. Daima, Emerging trends, and prospects in Nanozyme engineering to enhance dual-mode sensing applications, Coordination Chemistry Reviews, 2025, 540, 216768. https://doi.org/10.1016/j.ccr.2025.216768.
21. A. Baranwal, R. Shukla and V. Bansal, Nanozyme-enhanced paper-based biosensor technologies, TrAC Trends in Analytical Chemistry, 2024, 172, 117573. https://doi.org/10.1016/j.trac.2024.117573.
22. R. Singh, A. Umapathi, G. Patel, C. Patra, U. Malik, S. K. Bhargava and H. K. Daima, Nanozyme-based pollutant sensing and environmental treatment: Trends, challenges, and perspectives, Science of The Total Environment, 2023, 854, 158771. https://doi.org/10.1016/j.scitotenv.2022.158771.
23. L. Yang, X. Xu, Y. Song, J. Huang and H. Xu, Research progress of nanozymes in colorimetric biosensing: Classification, activity and application, Chemical Engineering Journal, 2024, 487, 150612. https://doi.org/10.1016/j.cej.2024.150612.
24. R. Zhang, X. Yan and K. Fan, Nanozymes Inspired by Natural Enzymes, Accounts of Materials Research, 2021, 2, 534–547. 10.1021/accountsmr.1c00074.
25. M. Liang and X. Yan, Nanozymes: From New Concepts, Mechanisms, and Standards to Applications, Accounts of Chemical Research, 2019, 52, 2190–2200. 10.1021/acs.accounts.9b00140.
26. R. Zhang, X. Yan, L. Gao and K. Fan, Nanozymes expanding the boundaries of

View Article Online
DOI: 10.1039/D5TA09692H

biocatalysis, Nature Communications, 2025, 16, 6817. 10.1038/s41467-025-62063-8.

27. I. Algov, A. Feiertag and L. Alfonta, Site-specifically wired and oriented glucose dehydrogenase fused to a minimal cytochrome with high glucose sensing sensitivity, Biosens Bioelectron, 2021, 180, 113117. 10.1016/j.bios.2021.113117.

28. K. Ito, J. Okuda-Shimazaki, K. Kojima, K. Mori, W. Tsugawa, R. Asano, K. Ikebukuro and K. Sode, Strategic design and improvement of the internal electron transfer of heme b domain-fused glucose dehydrogenase for use in direct electron transfer-type glucose sensors, Biosens Bioelectron, 2021, 176, 112911. 10.1016/j.bios.2020.112911.

29. M. Zandieh and J. Liu, Nanozymes: Definition, Activity, and Mechanisms, Advanced Materials, 2024, 36, 2211041. https://doi.org/10.1002/adma.202211041.

30. Y. Zhang, Y. Yang, Z. Yin, L. Huang and J. Wang, Nanozyme-based wearable biosensors for application in healthcare, iScience, 2025, 28, 111763. https://doi.org/10.1016/j.isci.2025.111763.

31. X. Li, J. Chen and S. Dong, Nanozymes for Energy and Environmental Sustainability, Advanced Science, 2026, 13, e19402. https://doi.org/10.1002/advs.202519402.

32. L. Singh, A. Sharma and J. Verma, Emerging green-synthesized nanozymes for microbial applications: toward sustainable antimicrobial technologies, World Journal of Microbiology and Biotechnology, 2025, 41, 444. 10.1007/s11274-025-04655-6.

33. F. Li, C. Zhou, J. Zhao, K. Li, M. Yang, N. Cheng, L. Qiu, J. Zhou and L. Li, Nanozyme taxonomy, mechanistic insights, and controllable synthesis strategies: Advances in precision agricultural applications, Chemical Engineering Journal, 2025, 525, 169555. https://doi.org/10.1016/j.cej.2025.169555.

34. Y. Zhang, G. Tian, J. Lin, Y. Fu and Y. Li, Nanozymes to Enhance Plant Photosynthesis: Mechanisms, Applications, and Future Prospects, Journal of Agricultural and Food Chemistry, 2026, 74, 6593–6611. 10.1021/acs.jafc.5c12837.

35. H. Kim, D. Kim, J. Lee, G. M. Rani, Y. Park, S. Han, H. Jeong, K. Shin, T. J. Park, R. Umapathi and Y. S. Huh, Beyond general catalysis: overcoming the specificity limitations of nanozyme for organic contaminants detection, Coordination Chemistry Reviews, 2026, 559, 217700. https://doi.org/10.1016/j.ccr.2026.217700.

36. B. R. Putra, E. Nurwidayanti, S. Fadilah, M. Khalil, E. Rustami and W. T. Wahyuni,

View Article Online
DOI: 10.1039/D5TA09692H

MWCNT-OH/graphene composite sensor for nonenzymatic detection of paraoxon-ethyl in agricultural samples, Carbon Letters, 2025, 35, 1291–1310. 10.1007/s42823-025-00868-9.

37. Y. Jia, L. Kang, Y. Wu, C. Zhou, D. Li, J. Li and C. Pan, Review on Pesticide Abiotic Stress over Crop Health and Intervention by Various Biostimulants, Journal of Agricultural and Food Chemistry, 2023, 71, 13595–13611. 10.1021/acs.jafc.3c04013.

38. V. M. Pathak, V. K. Verma, B. S. Rawat, B. Kaur, N. Babu, A. Sharma, S. Dewali, M. Yadav, R. Kumari, S. Singh, A. Mohapatra, V. Pandey, N. Rana and J. M. Cunill, Current status of pesticide effects on environment, human health and it's eco-friendly management as bioremediation: A comprehensive review, Frontiers in Microbiology, 2022, Volume 13 - 2022, 10.3389/fmicb.2022.962619.

39. R. Bhoi, C. Sahu and A. Pradhan, A global review on health risks of pesticide contamination in rice-based agricultural systems, Discover Applied Sciences, 2025, 7, 1316. 10.1007/s42452-025-07800-w.

40. W. Zhou, M. Li and V. Achal, A comprehensive review on environmental and human health impacts of chemical pesticide usage, Emerging Contaminants, 2025, 11, 100410. https://doi.org/10.1016/j.emcon.2024.100410.

41. A. Santana-Mayor, R. Rodríguez-Ramos, A. V. Herrera-Herrera, B. Socas-Rodríguez and M. A. Rodríguez-Delgado, Updated overview of QuEChERS applications in food, environmental and biological analysis (2020–2023), TrAC Trends in Analytical Chemistry, 2023, 169, 117375. https://doi.org/10.1016/j.trac.2023.117375.

42. L. Kim, D. Lee, H.-K. Cho and S.-D. Choi, Review of the QuEChERS method for the analysis of organic pollutants: Persistent organic pollutants, polycyclic aromatic hydrocarbons, and pharmaceuticals, Trends in Environmental Analytical Chemistry, 2019, 22, e00063. https://doi.org/10.1016/j.teac.2019.e00063.

43. S. Niell, V. Cesio, J. Hepperle, D. Doerk, L. Kirsch, D. Kolberg, E. Scherbaum, M. Anastassiades and H. Heinzen, QuEChERS-Based Method for the Multiresidue Analysis of Pesticides in Beeswax by LC-MS/MS and GC×GC-TOF, Journal of Agricultural and Food Chemistry, 2014, 62, 3675–3683. 10.1021/jf405771t.

44. M. Li, C. Dai, F. Wang, Z. Kong, Y. He, Y. T. Huang and B. Fan, Chemometric-assisted QuEChERS extraction method for post-harvest pesticide determination in fruits and vegetables, Scientific Reports, 2017, 7, 42489. 10.1038/srep42489.

45. J.-H. Joo, S.-H. Kim, J. H. Kim, H.-J. Kang, J. H. Lee, H.-J. Jeon, Y. H. Jang, J.-H. Lee, S.-Y. Lee, S.-J. Park and M.-K. Seo, Recent advances in activated carbon fibers for

View Article Online
DOI: 10.1039/D5TA09692H

pollutant removal, Carbon Letters, 2025, 35, 21–44. 10.1007/s42823-024-00803-4.

46. X. Lin, Y. Huang, J. Zou, G. Zhu, L. Pang and Y. Chen, Recent advances in nanozymes for organophosphorus pesticide detection in food, Chemical Communications, 2025, 61, 14510–14530. 10.1039/D5CC03464G.

47. A. M. Ashrafi, Z. Bytesnikova, J. Barek, L. Richtera and V. Adam, A critical comparison of natural enzymes and nanozymes in biosensing and bioassays, Biosensors and Bioelectronics, 2021, 192, 113494. https://doi.org/10.1016/j.bios.2021.113494.

48. S. Liu, J. Zhou, X. Yuan, J. Xiong, M.-H. Zong, X. Wu and W.-Y. Lou, A dual-mode sensing platform based on metal–organic framework for colorimetric and ratiometric fluorescent detection of organophosphorus pesticide, Food Chemistry, 2024, 432, 137272. https://doi.org/10.1016/j.foodchem.2023.137272.

49. X. Xu, T. Sun, X. Zhou, Z. Liu and L. Zhang, Specific and enzyme-free monitoring of propiconazole pesticide residues in vegetables with a portable nanozyme-based paper sensor, Food Chemistry, 2025, 464, 141686. https://doi.org/10.1016/j.foodchem.2024.141686.

50. X. Yan, R. Zou, Q. Lin, Y. Ma, A. Li, X. Sun, G. Lu and H. Li, Glutathione-iron hybrid nanozyme-based colorimetric sensor for specific and stable detection of thiram pesticide on fruit juices, Food Chemistry, 2024, 452, 139569. https://doi.org/10.1016/j.foodchem.2024.139569.

51. C. Jin, S. Yang, J. Zheng, F. Chai and M. Tian, A smartphone-assisted portable on-site detection system for organophosphorus pesticides in vegetables and fruits based on all-in-one paper-based sensors: 2,2-Dichlorovinyl dimethyl phosphate as a model, Food Chemistry, 2024, 459, 140369. https://doi.org/10.1016/j.foodchem.2024.140369.

52. T. Tian, D. Song, L. Zhang, H. Huang and Y. Li, Facile and selective recognition of sulfonylurea pesticides based on the multienzyme-like activities enhancement of nanozymes combining sensor array, Journal of Hazardous Materials, 2024, 469, 133847. https://doi.org/10.1016/j.jhazmat.2024.133847.

53. Q. Ma, S. Shen, X. Hou, H. Gong, Y. Zhou, T. Liu and X. Wang, Multi-functional colorimetric sensor arrays for accurate discrimination/quantitation of organophosphorus pesticides based on enhanced bienzymatic activity independent of routine peroxidase mimetics of V2O5-NC with C-O bridges-connected wide interlayer-spacing, Chemical Engineering Journal, 2025, 509,

View Article Online
DOI: 10.1039/D5TA09692H

161222. https://doi.org/10.1016/j.cej.2025.161222.

54. Z. Liu, Y. Feng, Y. Cui, Y. Wang, Z. Fu, J. Zhao, H. Li and C. Sun, Tuning ligand substituents of metal-organic frameworks enhances laccase-like activity for pesticide detection, Food Chemistry, 2025, 488, 144892. https://doi.org/10.1016/j.foodchem.2025.144892.

55. Y. Shen, X. Gao, H. Chen, Y. Wei, H. Yang and Y. Gu, Ultrathin C3N4 nanosheets-based oxidase-like 2D fluorescence nanozyme for dual-mode detection of organophosphorus pesticides, Journal of Hazardous Materials, 2023, 451, 131171. https://doi.org/10.1016/j.jhazmat.2023.131171.

56. T. Tian, D. Song, L. Zhen, Z. Bi, L. Zhang, H. Huang and Y. Li, Colorimetric – Fluorescence – Photothermal tri-mode sensor array combining the machine learning method for the selective identification of sulfonylurea pesticides, Biosensors and Bioelectronics, 2025, 277, 117286. https://doi.org/10.1016/j.bios.2025.117286.

57. Y. Bai, W. Gao, J. Wei, B. Yu, L. Zhang, P. Zhu and J. Yu, Biomimetic cascade intelligent paper chip sensor based on bimetallic porphyrin-based covalent organic framework with triple-enzyme mimetic activities, Chemical Engineering Journal, 2024, 490, 151628. https://doi.org/10.1016/j.cej.2024.151628.

58. D. Zhu, N. Li, M. Zhang, Y. Wang, F. Li and T. Hou, Hydrolysis enabled specific colorimetric assay of carbosulfan with sensitivity manipulation via metal-doped or metal-free carbon nanozyme, Biosensors and Bioelectronics, 2024, 243, 115786. https://doi.org/10.1016/j.bios.2023.115786.

59. T. Zhang, M. Tang, S. Yang, H. Fa, Y. Wang, D. Huo, C. Hou and M. Yang, Development of a novel ternary MOF nanozyme-based smartphone-integrated colorimetric and microfluidic paper-based analytical device for trace glyphosate detection, Food Chemistry, 2025, 464, 141780. https://doi.org/10.1016/j.foodchem.2024.141780.

60. X. Wang, X. Zang, X. Wang, W. Zhang, Y. Fang and B. Cui, Molecularly imprinted electrochemiluminescence-colorimetric dual-mode sensor based on Mn@NC nanozyme amplification for the detection of phoxim, Chemical Engineering Journal, 2024, 500, 156817. https://doi.org/10.1016/j.cej.2024.156817.

61. J. Guo, F. Zhao, Z. Yue and Z. Lei, Acetylcholinesterase-free colorimetric sensing platform for carbosulfan detection based on hollow PDA/MnO2 nanozyme, Food Chemistry, 2025, 465, 142075. https://doi.org/10.1016/j.foodchem.2024.142075.

View Article Online
DOI: 10.1039/D5TA09692H

62. Y. Ren, L. Cao, H. Li, R. Jiao, Y. Zhan, X. Zhang, X. Yu, M. Li, W. Wu, Z. Liang, G. Li, X. Xia, D. Zhang, N. Ling and Y. Ye, Trimetal–Organic Framework-Derived Diatomic Nanozymes-Driven Cascaded Signal Sensitization Intelligent Flexible Sensors for In Situ Detection of the Pesticide Residue, ACS Nano, 2025, 19, 23703–23718. 10.1021/acsnano.5c03245.

63. N. Guo, L. Jiao, L. Hu, D. Yan, C. Chen, P. Zong, X. Shi, Y. Zhai, Z. Zhu and X. Lu, Deciphering Pyridinic N−Mediated Inhibition Mode in Platinum Nanozymes for Pesticide Distinction, Small, 2025, 21, 2505731. https://doi.org/10.1002/smll.202505731.

64. H. Zhu, B. Liu, J. Pan, L. Xu, J. Liu, P. Hu, D. Du, Y. Lin and X. Niu, Redox interference-free bimodal paraoxon sensing enabled by an aggregation-induced emission nanozyme catalytically hydrolyzing phosphoesters specifically, Biosensors and Bioelectronics, 2025, 267, 116756. https://doi.org/10.1016/j.bios.2024.116756.

65. J. Li, M. Gao, X. Xia, Y. Cen, F. Wei, J. Yang, L. Wang, Q. Hu and G. Xu, Spherical Hydrogel Sensor Based on PB@Fe-COF@Au Nanoparticles with Triplet Peroxidase-like Activity and Multiple Capture Sites for Effective Detection of Organophosphorus Pesticides, ACS Applied Materials & Interfaces, 2023, 15, 6473–6485. 10.1021/acsami.2c19921.

66. D. Li, J. Li, C. Wu, H. Liu, M. Zhao, H. Shi, Y. Zhang and T. Wang, Smartphone-assisted colorimetric biosensor for the determination of organophosphorus pesticides on the peel of fruits, Food Chemistry, 2024, 443, 138459. https://doi.org/10.1016/j.foodchem.2024.138459.

67. J. Ge, L. Yang, Z. Li, Y. Wan, D. Mao, R. Deng, Q. Zhou, Y. Yang and W. Tan, A colorimetric smartphone-based platform for pesticides detection using Fe-N/C single-atom nanozyme as oxidase mimetics, Journal of Hazardous Materials, 2022, 436, 129199. https://doi.org/10.1016/j.jhazmat.2022.129199.

68. Y. Guo, X. Li, P. Shen, X. Li, Y. Cheng and K. Chu, Dendritic-like MXene quantum dots@CuNi as an efficient peroxidase candidate for colorimetric determination of glyphosate, Journal of Colloid and Interface Science, 2024, 661, 533–543. https://doi.org/10.1016/j.jcis.2024.01.177.

69. M. Sun, L. Zhao, T. Liu, Z. Lu, G. Su, C. Wu, C. Song, R. Deng, M. He, H. Rao and Y. Wang, Construction of CuO/Fe2O3 Nanozymes for Intelligent Detection of Glufosinate and Chlortetracycline Hydrochloride, ACS Applied Materials & Interfaces, 2023, 15, 54466–54477. 10.1021/acsami.3c12157.

View Article Online
DOI: 10.1039/D5TA09692H

70. Y. Zhang, J. Yang, W. Gao, S. G. Liu, Q. Zhao, Z. Fu and X. Shi, A smartphone-integrated colorimetric sensor for sensitive detection of organophosphorus pesticides based on large-scale synthesized Fe-N/C single-atom nanozymes, Sensors and Actuators B: Chemical, 2024, 403, 135130. https://doi.org/10.1016/j.snb.2023.135130.

71. A. Li, H. Li, Y. Ma, T. Wang, X. Liu, C. Wang, F. Liu, P. Sun, X. Yan and G. Lu, Bioinspired laccase-mimicking catalyst for on-site monitoring of thiram in paper-based colorimetric platform, Biosensors and Bioelectronics, 2022, 207, 114199. https://doi.org/10.1016/j.bios.2022.114199.

72. X. Zhan, Z. Ding, F. Liu, K. Chu and Y. Guo, Synthesis of MXene quantum dot-modified urchin-like NiCoP/NF nanostructures as high-performance peroxidase mimics for sensitive colorimetric detection of glyphosate, Food Chemistry, 2025, 489, 144966. https://doi.org/10.1016/j.foodchem.2025.144966.

73. M. Zhang, Y. Wang, N. Li, D. Zhu and F. Li, Specific detection of fungicide thiophanate-methyl: A smartphone colorimetric sensor based on target-regulated oxidase-like activity of copper-doped carbon nanozyme, Biosensors and Bioelectronics, 2023, 237, 115554. https://doi.org/10.1016/j.bios.2023.115554.

74. Z. Shen, D. Xu, G. Wang, L. Geng, R. Xu, G. Wang, Y. Guo and X. Sun, Novel colorimetric aptasensor based on MOF-derived materials and its applications for organophosphorus pesticides determination, Journal of Hazardous Materials, 2022, 440, 129707. https://doi.org/10.1016/j.jhazmat.2022.129707.

75. X. Luo, G. Huang, C. Bai, C. Wang, Y. Yu, Y. Tan, C. Tang, J. Kong, J. Huang and Z. Li, A versatile platform for colorimetric, fluorescence and photothermal multi-mode glyphosate sensing by carbon dots anchoring ferrocene metal-organic framework nanosheet, Journal of Hazardous Materials, 2023, 443, 130277. https://doi.org/10.1016/j.jhazmat.2022.130277.

76. Z. Yan, J. Zhong, Z. Liao, P. Xu and P. Qiu, Single-enzymatic (AChE/ChOx) colorimetric detection of organophosphorus pesticides based on controllable nanoparticles supported by FeCoCu flower-like structure with peroxidase-like activity, Sensors and Actuators B: Chemical, 2025, 424, 136878. https://doi.org/10.1016/j.snb.2024.136878.

77. M. Sun, S. Huang, G. Su, X. Wang, Z. Lu, Y. Wang, T. Liu, Y. Jiang, C. Song and H. Rao, Synthesis of pH-switchable Pt/Co3O4 nanoflowers: Catalytic mechanism, four-enzyme activity and smartphone biosensing applications, Chemical

View Article Online
DOI: 10.1039/D5TA09692H

Engineering Journal, 2022, 437, 134414. https://doi.org/10.1016/j.cej.2021.134414.

78. H. Zhu, P. Liu, L. Xu, X. Li, P. Hu, B. Liu, J. Pan, F. Yang and X. Niu, Nanozyme-Participated Biosensing of Pesticides and Cholinesterases: A Critical Review, Biosensors (Basel), 2021, 11, 10.3390/bios11100382.

79. Y. Huang, J. Ren and X. Qu, Nanozymes: Classification, Catalytic Mechanisms, Activity Regulation, and Applications, Chemical Reviews, 2019, 119, 4357–4412. 10.1021/acs.chemrev.8b00672.

80. R. Hou, N. Yin, Y. Wang, S. Song and H. Zhang, Nanozymes: recent advances for sustainable agricultural development, Nanoscale Horizons, 2025, https://doi.org/10.1039/D5NH00281H10.1039/D5NH00281H.

81. A. Shamsabadi, T. Haghighi, S. Carvalho, L. C. Frenette and M. M. Stevens, The Nanozyme Revolution: Enhancing the Performance of Medical Biosensing Platforms, Advanced Materials, 2024, 36, 2300184. https://doi.org/10.1002/adma.202300184.

82. S. Nayak, M. Aggarwal and P. Das, Bromine-doped carbon dot: concentration-dependent multicolor emission, nanozyme activity, and visible-light-induced photodynamic bacterial inactivation, Carbon Letters, 2025, 35, 593–605. 10.1007/s42823-024-00796-0.

83. Y. Ouyang, M. P. O'Hagan and I. Willner, Functional catalytic nanoparticles (nanozymes) for sensing, Biosensors and Bioelectronics, 2022, 218, 114768. https://doi.org/10.1016/j.bios.2022.114768.

84. E. M. Hamed, K. Kustomo, M. M. ElSaady, X. Wu, F. M. Fung and S. F. Y. Li, Organic-Dominated Nanozymes for Pesticide Detection: Toward Sustainable Agricultural Monitoring, Journal of Agricultural and Food Chemistry, 2025, https://doi.org/10.1021/acs.jafc.5c0672110.1021/acs.jafc.5c06721.

85. M. Levine, Fluorescence-Based Sensing of Pesticides Using Supramolecular Chemistry, Frontiers in Chemistry, 2021, Volume 9 - 2021, 10.3389/fchem.2021.616815.

86. G. Kalaiarasi, A. Shanmughan, Y. Jegadeesan, M. K. Noushija, A. V. Krishna, H. Gangadharan, D. Umadevi and S. Shanmugaraju, Recent progress in fluorescence-based chemosensing of pesticides, Sensors & Diagnostics, 2025, 4, 460–488. 10.1039/d4sd00364k.

87. S. Paul, P. Daga and N. Dey, Exploring Various Photochemical Processes in Optical Sensing of Pesticides by Luminescent Nanomaterials: A Concise Discussion on

View Article Online
DOI: 10.1039/D5TA09692H

Challenges and Recent Advancements, ACS Omega, 2023, 8, 44395–44423. 10.1021/acsomega.3c02753.

88. S. Zhang, Z. Wang, Y. Feng, C. Jiang, H. Li, Z. Yu, Y. Xiao, R. Hou, X. Wan and Y. Liu, A novel fluorescent and photothermal probe based on nanozyme-mediated cascade reaction for detecting organophosphorus pesticide residues, Talanta, 2024, 279, 126620. https://doi.org/10.1016/j.talanta.2024.126620.

89. J. Wu, Q. Yang, Q. Li, H. Li and F. Li, Two-Dimensional MnO2 Nanozyme-Mediated Homogeneous Electrochemical Detection of Organophosphate Pesticides without the Interference of H2O2 and Color, Analytical Chemistry, 2021, 93, 4084–4091. 10.1021/acs.analchem.0c05257.

90. F. Faghiri, M. Hajjami and F. Ghorbani, Development of a sensing system based on coupling magnetic solid phase extraction and colorimetric detection for determination of organophosphorus pesticides in fruit extract and environmental sample, Sensors and Actuators B: Chemical, 2021, 343, 130157. https://doi.org/10.1016/j.snb.2021.130157.

91. D. Song, L. Lei, T. Tian, X. Yang, L. Wang, Y. Li and H. Huang, A novel strategy for identification of pesticides in different categories by concentration-independent model based on a nanozyme with multienzyme-like activities, Biosensors and Bioelectronics, 2023, 237, 115458. https://doi.org/10.1016/j.bios.2023.115458.

92. H. Wu, J.-H. Li, W.-C. Yang, T. Wen, J. He, Y.-Y. Gao, G.-F. Hao and W.-C. Yang, Nonmetal-doped quantum dot-based fluorescence sensing facilitates the monitoring of environmental contaminants, Trends in Environmental Analytical Chemistry, 2023, 40, e00218. https://doi.org/10.1016/j.teac.2023.e00218.

93. W. Hu, Q. Chen, H. Li, Q. Ouyang and J. Zhao, Fabricating a novel label-free aptasensor for acetamiprid by fluorescence resonance energy transfer between NH2-NaYF4: Yb, Ho@SiO2 and Au nanoparticles, Biosensors and Bioelectronics, 2016, 80, 398–404. https://doi.org/10.1016/j.bios.2016.02.001.

94. Z.-D. Zhou, C.-Y. Wang, G.-S. Zhu, B. Du, B.-Y. Yu and C.-C. Wang, Water-stable europium(III) and terbium(III)-metal organic frameworks as fluorescent sensors to detect ions, antibiotics and pesticides in aqueous solutions, Journal of Molecular Structure, 2022, 1251, 132009. https://doi.org/10.1016/j.molstruc.2021.132009.

95. H. Qiu, H. Yang, X. Gao, C. Nie, Y. Gu and Y. Shen, Inner filter effect-based fluorescence assays toward environmental pesticides and antibiotics, Coordination Chemistry Reviews, 2023, 493, 215305. https://doi.org/10.1016/j.ccr.2023.215305.

View Article Online
DOI: 10.1039/D5TA09692H

96. S. Li, J. Wu, S. Zhang, T. Jiao, J. Wei, X. Chen, Q. Chen and Q. Chen, Inner filter effect-based upconversion nanosensor for rapid detection of thiram pesticides using upconversion nanoparticles and dithizone–cadmium complexes, Food Chemistry, 2024, 434, 137438. https://doi.org/10.1016/j.foodchem.2023.137438.

97. S. Tripathi and M. Chakravarty, Efficient dual-phase visual detection of pesticides in real samples with electron-rich emitters carrying multiple twists, Materials Advances, 2025, 6, 5928–5939. 10.1039/d5ma00630a.

98. D. Escudero, Revising Intramolecular Photoinduced Electron Transfer (PET) from First-Principles, Accounts of Chemical Research, 2016, 49, 1816–1824. 10.1021/acs.accounts.6b00299.

99. Y.-S. Chen, Z.-W. Chen, Y.-W. Yuan, K.-C. Chen and C.-P. Liu, Fluorescence Quenchers Manipulate the Peroxidase-like Activity of Gold-Based Nanomaterials, ACS Omega, 2020, 5, 24487–24494. 10.1021/acsomega.0c02956.

100. Y. Chang, Z. Zhang, J. Hao, W. Yang and J. Tang, A simple label free colorimetric method for glyphosate detection based on the inhibition of peroxidase-like activity of Cu(Ⅱ), Sensors and Actuators B: Chemical, 2016, 228, 410–415. https://doi.org/10.1016/j.snb.2016.01.048.

101. M. Zhu, X. Zhu, M. Chen, X. Pang, Y. Hong and Y. Wang, A novel Cu2+-coordinated fluorescent sensing system for specific detection of glyphosate and its applications in environmental and biological systems, Journal of Hazardous Materials, 2025, 488, 137424. https://doi.org/10.1016/j.jhazmat.2025.137424.

102. X. Li, Z. Wang, J. He, H. Al-Mashriqi, J. Chen and H. Qiu, Recent advances in emerging nanozymes with aggregation-induced emission, Chemical Science, 2025, 16, 29–42. 10.1039/D4SC05709K.

103. Y. Huang, L. Gong, C. Xie, W. Qin, M. Wang, L. Hu and Z. Xia, Anchoring biomimetic Zn site in metal–organic framework nanozyme to enhance phosphatase-like catalytic activity for discrimination of organophosphorus pesticides, Chemical Engineering Journal, 2025, 506, 160046. https://doi.org/10.1016/j.cej.2025.160046.

104. D. Song, T. Tian, L. Wang, Y. Zou, L. Zhao, J. Xiao, H. Huang and Y. Li, Multi-signal sensor array based on a fluorescent nanozyme for broad-spectrum screening of pesticides, Chemical Engineering Journal, 2024, 482, 148784. https://doi.org/10.1016/j.cej.2024.148784.

105. S.-H. Wen, H. Zhang, S. Yu, J. Ma, J.-J. Zhu and Y. Zhou, Nanozyme coating-gated

View Article Online
DOI: 10.1039/D5TA09692H

multifunctional COF composite based dual-ratio enhanced dual-mode sensor for highly sensitive and reliable detection of organophosphorus pesticides in real samples, Journal of Hazardous Materials, 2024, 480, 135791. https://doi.org/10.1016/j.jhazmat.2024.135791.

106. J. Liu, X. Yu, Y. Zhou, L. Sun, Y. Liu and J. Li, Breaking the conventional: Ligand-triggered Zn-MOF nanozyme with unusual oxidase activity for dual-channel sensing of benfuracarb, Biosensors and Bioelectronics, 2025, 280, 117441. https://doi.org/10.1016/j.bios.2025.117441.

107. C.-L. Yang, L.-H. Yu, Y.-H. Pang and X.-F. Shen, A ratiometric fluorescence sensor for detection of organophosphorus pesticides based on enzyme-regulated multifunctional Fe-based metal-organic framework, Talanta, 2024, 278, 126516. https://doi.org/10.1016/j.talanta.2024.126516.

108. J.-J. Zhu, H.-Y. Niu, C. Yi, K.-X. Wang and C.-G. Niu, Dual-mode detection of malathion under neutral conditions: Integrated application of specific nanozyme and time-resolved europium probe, Sensors and Actuators B: Chemical, 2025, 435, 137650. https://doi.org/10.1016/j.snb.2025.137650.

109. Z. Ding, X. Zhan, F. Liu, K. Chu and Y. Guo, MXene quantum dots coupled with amorphous CoOX: A high-performance peroxidase mimic for direct detection of the pesticide profenofos, Food Bioscience, 2025, 68, 106658. https://doi.org/10.1016/j.fbio.2025.106658.

110. S. Liu, H. Yu, S. Zhu and X.-E. Zhao, Copper-based fluorescent nanozyme used to construct a ratiometric sensor for visual detection of thiophanate methyl, Talanta, 2025, 285, 127417. https://doi.org/10.1016/j.talanta.2024.127417.

111. J. Wang, Y. Huang, Z. Kuai, Y. Zhang, Q. Shen, P. Tian, W. Nong, W. Jiang, Y. He, N. Ran, Y. Yin, T. Li and Q. Luo, Ultrasensitive and rapid detection of organophosphates using a dual-signal naked-eye hydrogel sensor based on acetylcholinesterase inhibition, International Journal of Biological Macromolecules, 2024, 283, 137778. https://doi.org/10.1016/j.ijbiomac.2024.137778.

112. Y. Zhao, H. Chen, C. Chang, L. Xu and L. Han, Clusterization-triggered emission artificial enzyme (CTEzyme) with specific activity inhibition boosting ratiometric fluorescence detection of pesticide, Sensors and Actuators B: Chemical, 2025, 432, 137491. https://doi.org/10.1016/j.snb.2025.137491.

113. Y. Zhang, L. Xue, F. Du, S. Yang, T. Liu, T. Wu and X. Jiang, Synergistic ultrasensitive detection of paraoxon via a photoelectrochemical-fluorescent dual-

View Article Online
DOI: 10.1039/D5TA09692H

mode aptasensor with S-scheme Zn0.1Cd0.9S/Cu2MoS4 heterostructure and Zr-MOF nanozyme, Sensors and Actuators B: Chemical, 2026, 449, 139164. https://doi.org/10.1016/j.snb.2025.139164.

114. N. Bagheri, A. Khataee, J. Hassanzadeh and B. Habibi, Sensitive biosensing of organophosphate pesticides using enzyme mimics of magnetic ZIF-8, Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 2019, 209, 118–125. https://doi.org/10.1016/j.saa.2018.10.039.

115. V. G. Panferov and J. Liu, Optical and Catalytic Properties of Nanozymes for Colorimetric Biosensors: Advantages, Limitations, and Perspectives, Advanced Optical Materials, 2024, 12, 2401318. https://doi.org/10.1002/adom.202401318.

116. D. Luo, X. Huang, B. Liu, W. Zou and Y. Wu, Facile Colorimetric Nanozyme Sheet for the Rapid Detection of Glyphosate in Agricultural Products Based on Inhibiting Peroxidase-Like Catalytic Activity of Porous Co3O4 Nanoplates, Journal of Agricultural and Food Chemistry, 2021, 69, 3537–3547. 10.1021/acs.jafc.0c08208.

117. P. Weerathunge, R. Ramanathan, R. Shukla, T. K. Sharma and V. Bansal, Aptamer-Controlled Reversible Inhibition of Gold Nanozyme Activity for Pesticide Sensing, Analytical Chemistry, 2014, 86, 11937–11941. 10.1021/ac5028726.

118. Z. Wu, Z. Hao, Y. Chai, A. Li, C. Wang, X. Zhang, H. Chen and C. Lu, Near-infrared-excitable acetylcholinesterase-activated fluorescent probe for sensitive and anti-interference detection of pesticides in colored food, Biosensors and Bioelectronics, 2023, 233, 115341. https://doi.org/10.1016/j.bios.2023.115341.

119. D. Li, S. L. Garisto, P.-J. J. Huang, J. Yang, B. Liu and J. Liu, Fluorescent detection of fluoride by CeO2 nanozyme oxidation of Amplex red, Inorganic Chemistry Communications, 2019, 106, 38–42. 10.1016/j.inoche.2019.05.028.

120. C. Shang, Q. Wang, H. Tan, S. Lu, S. Wang, Q. Zhang, L. Gu, J. Li, E. Wang and S. Guo, Defective PtRuTe As Nanozyme with Selectively Enhanced Peroxidase-like Activity, JACS Au, 2022, 2, 2453–2459. 10.1021/jacsau.2c00495.

121. J. Wei, L. Yang, M. Luo, Y. Wang and P. Li, Nanozyme-assisted technique for dual mode detection of organophosphorus pesticide, Ecotoxicology and Environmental Safety, 2019, 179, 17–23. https://doi.org/10.1016/j.ecoenv.2019.04.041.

122. D. Wei, M. Li, Y. Wang, N. Zhu, X. Hu, B. Zhao, Z. Zhang and D. Yin, Encapsulating gold nanoclusters into metal–organic frameworks to boost luminescence for sensitive detection of copper ions and organophosphorus pesticides, Journal of Hazardous Materials, 2023, 441, 129890.

View Article Online
DOI: 10.1039/D5TA09692H

https://doi.org/10.1016/j.jhazmat.2022.129890.

123. Q. Fu, S. Tian, S. Wang, G. Sun, M. Wang and K. Fan, Advances in Metal–Organic Framework-Based Nanozymes for Biosensing and Point-of-Care Testing Applications, ACS Applied Nano Materials, 2025, 8, 17339–17355. 10.1021/acsanm.5c02319.

124. S. Alagarsamy, B. Ramachandran and Y.-C. Liao, Next-generation electrochemical-optical sensors: Advanced and innovative strategies for pesticide detection, Chemical Engineering Journal, 2025, 520, 10.1016/j.cej.2025.166021.

125. B. M. da Costa Filho, A. C. Duarte and T. A. P. Rocha-Santos, Environmental monitoring approaches for the detection of organic contaminants in marine environments: A critical review, Trends in Environmental Analytical Chemistry, 2022, 33, 10.1016/j.teac.2022.e00154.

126. L. C. Clark, Jr. and C. Lyons, Electrode systems for continuous monitoring in cardiovascular surgery, Ann N Y Acad Sci, 1962, 102, 29–45. 10.1111/j.1749-6632.1962.tb13623.x.

127. C. Gu, S. Ji, Z. Chen, W. Yang, Y. Deng, M. Zhao, W. Huang, W. Yang and W. Xu, Enrichment-catalytic synergistically enhanced electrochemiluminescence sensors based on IRMOF-3/CdTe for ultrasensitive detection of organophosphorus pesticides, Biosens Bioelectron, 2025, 279, 117398. 10.1016/j.bios.2025.117398.

128. Q. Hou, M. Rooman and F. Pucci, Enzyme Stability-Activity Trade-Off: New Insights from Protein Stability Weaknesses and Evolutionary Conservation, J Chem Theory Comput, 2023, 19, 3664–3671. 10.1021/acs.jctc.3c00036.

129. A. Kunka, S. M. Marques, M. Havlasek, M. Vasina, N. Velatova, L. Cengelova, D. Kovar, J. Damborsky, M. Marek, D. Bednar and Z. Prokop, Advancing Enzyme's Stability and Catalytic Efficiency through Synergy of Force-Field Calculations, Evolutionary Analysis, and Machine Learning, ACS Catal, 2023, 13, 12506–12518. 10.1021/acscatal.3c02575.

130. L. Gao, J. Zhuang, L. Nie, J. Zhang, Y. Zhang, N. Gu, T. Wang, J. Feng, D. Yang, S. Perrett and X. Yan, Intrinsic peroxidase-like activity of ferromagnetic nanoparticles, Nature Nanotechnology, 2007, 2, 577–583. 10.1038/nnano.2007.260.

131. X. Zhu, L. Lin, R. Wu, Y. Zhu, Y. Sheng, P. Nie, P. Liu, L. Xu and Y. Wen, Portable wireless intelligent sensing of ultra-trace phytoregulator alpha-naphthalene acetic acid using self-assembled phosphorene/Ti(3)C(2)-MXene nanohybrid with high ambient stability on laser induced porous graphene as nanozyme flexible

View Article Online
DOI: 10.1039/D5TA09692H

electrode, Biosens Bioelectron, 2021, 179, 113062. 10.1016/j.bios.2021.113062.

132. W. Wu and J. Li, Recent progress on nanozymes in electrochemical sensing, Journal of Electroanalytical Chemistry, 2023, 936, 10.1016/j.jelechem.2023.117391.

133. W. Han, P. Wei, L. Xie, L. Zhu, B. He and X. Cao, Heteroatom modulation of nickel single-atom nanozymes for enhanced interfacial catalytic activity in sensitive electrochemical detection of herbicides, Chemical Engineering Journal, 2025, 505, 159557. https://doi.org/10.1016/j.cej.2025.159557.

134. L. Geng, X. Sun, L. Wang, F. Liu, S. Hu, S. Zhao and F. Ye, Analyte-induced laccase-mimicking activity inhibition and conductivity enhancement of electroactive nanozymes for ratiometric electrochemical detection of thiram, J Hazard Mater, 2024, 463, 132936. 10.1016/j.jhazmat.2023.132936.

135. K. Niu, J. Chen and X. Lu, Versatile biomimetic catalyst functionalized nanozymes for electrochemical sensing, Chemical Engineering Journal, 2023, 475, 10.1016/j.cej.2023.146491.

136. X. Ruan, Y. Wang, E. Y. Kwon, L. Wang, N. Cheng, X. Niu, S. Ding, B. J. Van Wie, Y. Lin and D. Du, Nanomaterial-enhanced 3D-printed sensor platform for simultaneous detection of atrazine and acetochlor, Biosensors and Bioelectronics, 2021, 184, 113238. https://doi.org/10.1016/j.bios.2021.113238.

137. H. Zeng, H. Chen, B. Yang, J. Zeng, L. Meng, D. Shi, L. Chen and Y. Huang, Highly-oxidizing Au@MnO(2-X) nanozymes mediated homogeneous electrochemical detection of organophosphorus independent of dissolved oxygen, J Hazard Mater, 2023, 459, 132116. 10.1016/j.jhazmat.2023.132116.

138. R. Wang, B. Li, G. Li, Q. Shen and L. Zou, NiCoFeS/rGO nanozyme-mediated multifunctional homogeneous sensing system for ultrasensitive electrochemical assay of pesticides residues in fruits and vegetables, Sensors and Actuators B: Chemical, 2025, 422, 10.1016/j.snb.2024.136664.

139. Y. Sun, J. Wei, J. Zou, Z. Cheng, Z. Huang, L. Gu, Z. Zhong, S. Li, Y. Wang and P. Li, Electrochemical detection of methyl-paraoxon based on bifunctional cerium oxide nanozyme with catalytic activity and signal amplification effect, J Pharm Anal, 2021, 11, 653–660. 10.1016/j.jpha.2020.09.002.

140. M. Khairy, H. A. Ayoub and C. E. Banks, Non-enzymatic electrochemical platform for parathion pesticide sensing based on nanometer-sized nickel oxide modified screen-printed electrodes, Food Chem, 2018, 255, 104–111. 10.1016/j.foodchem.2018.02.004.

View Article Online
DOI: 10.1039/D5TA09692H

141. G. Wang, J. Liu, H. Dong, L. Geng, J. Sun, J. Liu, J. Dong, Y. Guo and X. Sun, A dual-mode biosensor featuring single-atom Fe nanozyme for multi-pesticide detection in vegetables, Food Chem, 2024, 437, 137882. 10.1016/j.foodchem.2023.137882.
142. X. Zhang, N. Hao, S. Liu, K. Wei, C. Ma, J. Pan and S. Feng, Construction of phosphatase-like COF-OMe@Valine-CeO2 nanozymes for ultrasensitive electrochemical detection of organophosphorus pesticides, Sensors and Actuators B: Chemical, 2024, 417, 10.1016/j.snb.2024.136068.
143. X. Pang, G. I. N. Waterhouse, R. Wang, X. Qiao, Y. Sun and Z. Xu, Bifunctional ZrO2@ZIF-90 nanozyme with high phosphohydrolase activity for sensitive electrochemical detection of methyl parathion, Food Science and Human Wellness, 2025, 14, 9250095. 10.26599/FSHW.2024.9250095.
144. X. Zhang, C. Xue, H. Cao, Y. Wu, B. Yang, T. Zhou, W. Zhai and J. Deng, Ultra-small CuOx/GDYO nanozyme with boosting peroxidase-like activity via electrochemical strategy: Toward applicable colorimetric detection of organophosphate pesticides, Talanta, 2024, 279, 126639. https://doi.org/10.1016/j.talanta.2024.126639.
145. L. Yu, J. Chang, X. Zhuang, H. Li, T. Hou and F. Li, Two-Dimensional Cobalt-Doped Ti(3)C(2) MXene Nanozyme-Mediated Homogeneous Electrochemical Strategy for Pesticides Assay Based on In Situ Generation of Electroactive Substances, Anal Chem, 2022, 94, 3669–3676. 10.1021/acs.analchem.1c05300.
146. C. Praharaj, S. Singh, P. Tripathi and S. Nara, Investigating gold nanorod-mediated hydrolysis of acetylthiocholine: a way for electrochemical detection of organophosphate pesticides, Environmental Science: Nano, 2025, 12, 1558–1569. 10.1039/d4en00913d.
147. G. Chen, G. Liu, H. Jia, X. Cui, Y. Wang, D. Li, W. Zheng, Y. She, D. Xu, X. Huang, A. M. Abd El-Aty, J. Sun, H. Liu, Y. Zou, J. Wang, M. Jin and B. D. Hammock, A sensitive bio-barcode immunoassay based on bimetallic Au@Pt nanozyme for detection of organophosphate pesticides in various agro-products, Food Chem, 2021, 362, 130118. 10.1016/j.foodchem.2021.130118.
148. M. Zandieh and J. Liu, Nanozyme Catalytic Turnover and Self-Limited Reactions, ACS Nano, 2021, 15, 15645–15655. 10.1021/acsnano.1c07520.
149. Z. Yang, J. Guo, L. Wang, J. Zhang, L. Ding, H. Liu and X. Yu, Nanozyme-Enhanced Electrochemical Biosensors: Mechanisms and Applications, Small, 2024, 20, e2307815. 10.1002/smll.202307815.

View Article Online
DOI: 10.1039/D5TA09692H

150. Q. Liu, A. Zhang, R. Wang, Q. Zhang and D. Cui, A Review on Metal- and Metal Oxide-Based Nanozymes: Properties, Mechanisms, and Applications, Nanomicro Lett, 2021, 13, 154. 10.1007/s40820-021-00674-8.

151. Z. Guo, J. Hong, N. Song and M. Liang, Single-Atom Nanozymes: From Precisely Engineering to Extensive Applications, Accounts of Materials Research, 2024, 5, 347–357. 10.1021/accountsmr.3c00250.

152. Q. Zhao, X. Zheng, L. Xing, Y. Tang, X. Zhou, L. Hu, W. Yao and Z. Yan, 2D Co(3)O(4) stabilizing Rh nano composites developed for visual sensing bioactive urea and toxic p-aminophenol in practice by synergetic-reinforcing oxidase activity, J Hazard Mater, 2021, 409, 125019. 10.1016/j.jhazmat.2020.125019.

153. L. Fu, D. Yu, D. Zou, H. Qian and Y. Lin, Engineering the Stability of Nanozyme-Catalyzed Product for Colorimetric Logic Gate Operations, Molecules, 2021, 26, 10.3390/molecules26216494.

154. S. Li, C. Pang, X. Ma, Y. Zhang, Z. Xu, J. Li, M. Zhang and M. Wang, Microfluidic paper-based chip for parathion-methyl detection based on a double catalytic amplification strategy, Microchimica Acta, 2021, 188, 438. 10.1007/s00604-021-05084-6.

155. T. Sahare, N. Singh, B. N. Sahoo and A. Joshi, Smartphone-enhanced nanozyme sensors: Colorimetric and fluorescence sensing techniques, Biosensors and Bioelectronics: X, 2024, 21, 100544. https://doi.org/10.1016/j.biosx.2024.100544.

156. F. P. Gbonyea, J. Wu, M. Li, M. Liang, M. Zhang, X. Zhu, X. Li, S. He and P. Liu, Smartphone-integrated Nanozyme approaches for rapid and on-site detection: Empowering smart food safety, Food Chemistry, 2025, 486, 144678. https://doi.org/10.1016/j.foodchem.2025.144678.

157. H. Dong, W. Du, J. Dong, R. Che, F. Kong, W. Cheng, M. Ma, N. Gu and Y. Zhang, Depletable peroxidase-like activity of Fe(3)O(4) nanozymes accompanied with separate migration of electrons and iron ions, Nat Commun, 2022, 13, 5365. 10.1038/s41467-022-33098-y.

158. K. Fan, H. Wang, J. Xi, Q. Liu, X. Meng, D. Duan, L. Gao and X. Yan, Optimization of Fe(3)O(4) nanozyme activity via single amino acid modification mimicking an enzyme active site, Chem Commun (Camb), 2016, 53, 424–427. 10.1039/c6cc08542c.

159. H. Ouyang, Q. Lu, W. Wang, Y. Song, X. Tu, C. Zhu, J. N. Smith, D. Du, Z. Fu and Y. Lin, Dual-Readout Immunochromatographic Assay by Utilizing MnO2 Nanoflowers

View Article Online
DOI: 10.1039/D5TA09692H

as the Unique Colorimetric/Chemiluminescent Probe, Analytical Chemistry, 2018, 90, 5147–5152. 10.1021/acs.analchem.7b05247.

160. X. Zhang, C. Xue, H. Cao, Y. Wu, B. Yang, T. Zhou, W. Zhai and J. Deng, Ultra-small CuO(x)/GDYO nanozyme with boosting peroxidase-like activity via electrochemical strategy: Toward applicable colorimetric detection of organophosphate pesticides, Talanta, 2024, 279, 126639. 10.1016/j.talanta.2024.126639.

161. S. H. Wen, H. Zhang, S. Yu, J. Ma, J. J. Zhu and Y. Zhou, Nanozyme coating-gated multifunctional COF composite based dual-ratio enhanced dual-mode sensor for highly sensitive and reliable detection of organophosphorus pesticides in real samples, J Hazard Mater, 2024, 480, 135791. 10.1016/j.jhazmat.2024.135791.

162. J. Wu, Q. Yang, Q. Li, H. Li and F. Li, Two-Dimensional MnO(2) Nanozyme-Mediated Homogeneous Electrochemical Detection of Organophosphate Pesticides without the Interference of H(2)O(2) and Color, Anal Chem, 2021, 93, 4084–4091. 10.1021/acs.analchem.0c05257.

163. Y. Wang, Y. Liu, Z. Liu, X. Wang, M. Yu, G. Gao, Y. Zhao and J. Hong, A colorimetric-SERS sensor based on MXene nanosheets loaded with Fe3O4@Ag nanoparticles is used for sensitive and reliable detection of thiram, Microchimica Acta, 2026, 193, 270. 10.1007/s00604-026-07988-7.

164. L. Shang, S. Zhou, X. Zhang, J. Chen, S. Wen, D. Liu, M. Mu, B. Zhao and W. Song, Multiplexed discrimination and ultrasensitive determination of pesticides using a Cu-O-Mo nanozyme tri-channel array driven by machine learning, Biosensors and Bioelectronics, 2026, 297, 118374. https://doi.org/10.1016/j.bios.2026.118374.

165. Y. Chen, H. Liu, Y. Tian, Y. Du, Y. Ma, S. Zeng, C. Gu, T. Jiang and J. Zhou, In Situ Recyclable Surface-Enhanced Raman Scattering-Based Detection of Multicomponent Pesticide Residues on Fruits and Vegetables by the Flower-like MoS2@Ag Hybrid Substrate, ACS Applied Materials & Interfaces, 2020, 12, 14386–14399. 10.1021/acsami.9b22725.

166. H. Li, S. A. Haruna, W. Sheng, Q. Bei, W. Ahmad, M. Zareef, Q. Chen and Z. Ding, SERS-activated platforms for chemical contaminants in food: Probes, encoding methods, and detection, TrAC Trends in Analytical Chemistry, 2023, 169, 117365. https://doi.org/10.1016/j.trac.2023.117365.

167. A. Azzouz, V. Kumar, L. Hejji and K.-H. Kim, Advancements in nanomaterial-based aptasensors for the detection of emerging organic pollutants in environmental and biological samples, Biotechnology Advances, 2023, 66, 108156.

View Article Online
DOI: 10.1039/D5TA09692H

https://doi.org/10.1016/j.biotechadv.2023.108156.

168. T. Wu, Y. Mao, T. Wang, L. Ma, J. Cao, B. Xie, J. Wei and P. Li, Evolving trends in nanozyme-based SERS systems for food contaminant monitoring: A review, Food Chemistry, 2025, 486, 144621. https://doi.org/10.1016/j.foodchem.2025.144621.

169. X. Zhang, D. Wu, X. Zhou, Y. Yu, J. Liu, N. Hu, H. Wang, G. Li and Y. Wu, Recent progress in the construction of nanozyme-based biosensors and their applications to food safety assay, TrAC Trends in Analytical Chemistry, 2019, 121, 115668. https://doi.org/10.1016/j.trac.2019.115668.

170. V. Kumar, D. Bano, D. K. Singh, S. Mohan, V. K. Singh and S. H. Hasan, Size-Dependent Synthesis of Gold Nanoparticles and Their Peroxidase-Like Activity for the Colorimetric Detection of Glutathione from Human Blood Serum, ACS Sustainable Chemistry & Engineering, 2018, 6, 7662–7675. 10.1021/acssuschemeng.8b00503.

171. M. A. Abdel-Lateef, Utilization of the peroxidase-like activity of silver nanoparticles nanozyme on O-phenylenediamine/H2O2 system for fluorescence detection of mercury (II) ions, Scientific Reports, 2022, 12, 6953. 10.1038/s41598-022-10779-8.

172. X. Wang, X. Tang, C. Ji, L. Wu and Y. Zhu, Advances and Future Trends in Nanozyme-Based SERS Sensors for Food Safety, Environmental and Biomedical Applications, Int J Mol Sci, 2025, 26, 10.3390/ijms26020709.

173. Y. Yuan, J. Mi, Y. Cao, X. Hao, Y. Wu and J. Shi, A SERS sensing platform leveraging Fe-ZIF nanozyme activity inhibition for ultrasensitive glyphosate detection, Opto-Electronic Engineering, 2025, 52, 250115–250111–250115–250110. 10.12086/oee.2025.250115.

174. C. Li, F. Yu, J. Yang, H. Bai, X. Ma and Z. Jiang, SERS- and absorbance-based catalytic assay for determination of isocarbophos using aptamer-modified FeMOF nanozyme and in situ generated silver nanoparticles, Microchimica Acta, 2022, 190, 4. 10.1007/s00604-022-05549-2.

175. Y. He, R. Zhang, S. Xie, X. He, X. Yang, Y. Liu and M. Wang, A triple-mode strategy for ultrasensitive and accurate point-of-care detection of glyphosate based on the carved bimetallic prussian blue nanozyme and gold polyhedra, Journal of Food Composition and Analysis, 2025, 144, 107661. https://doi.org/10.1016/j.jfca.2025.107661.

176. M. Yan, G. Chen, Y. She, J. Ma, S. Hong, Y. Shao, A. M. Abd El-Aty, M. Wang, S. Wang and J. Wang, Sensitive and Simple Competitive Biomimetic Nanozyme-

View Article Online
DOI: 10.1039/D5TA09692H

Linked Immunosorbent Assay for Colorimetric and Surface-Enhanced Raman Scattering Sensing of Triazophos, Journal of Agricultural and Food Chemistry, 2019, 67, 9658–9666. 10.1021/acs.jafc.9b03401.

177. Y. Zhou, X. Liu, Y. Xu, Y. Jin, D. Wang and Y. Li, Sea-urchin-like Au@Pt nanozyme-mediated sensing platform on single gold nanowire: Fabrication, cascade catalytic amplification and highly sensitive dual-mode detection of organophosphorus pesticides, Sensors and Actuators B: Chemical, 2026, 459, 139881. https://doi.org/10.1016/j.snb.2026.139881.

178. Z. Wang, N. Liu, Y. Fan and A. Wu, Nanozyme-based biosensors for food contaminants detection: advances, challenges, and prospects, Talanta, 2025, 295, 128290. https://doi.org/10.1016/j.talanta.2025.128290.

179. Y. Zhuang, H. Yin, Y. Huang, F. Jiang, L. Li, Z. Wu, Y. Yang, X. Cao and W. Wei, Catalytic hairpin assembly-powered nanozyme-SERS dual-function sensing system for ultrasensitive detection of gastric precancerous lesions, Biosensors and Bioelectronics, 2025, 283, 117536. https://doi.org/10.1016/j.bios.2025.117536.

180. X. H. Pham, B. Seong, S. Bock, E. Hahm, K. H. Huynh, Y. H. Kim, W. Kim, J. Kim, D. E. Kim and B. H. Jun, Nonenzymatic Hydrogen Peroxide Detection Using Surface-Enhanced Raman Scattering of Gold-Silver Core-Shell-Assembled Silica Nanostructures, Nanomaterials (Basel), 2021, 11, 10.3390/nano11102748.

181. J. Jin, W. Song, J. Wang, L. Li, Y. Tian, S. Zhu, Y. Zhang, S. Xu, B. Yang and B. Zhao, A highly sensitive SERS platform based on small-sized Ag/GQDs nanozyme for intracellular analysis, Chemical Engineering Journal, 2022, 430, 132687. https://doi.org/10.1016/j.cej.2021.132687.

182. F. Zhao, W. Wu, M. Zhao, S. Ding, Y. Lin, Q. Hu and L. Yu, Enzyme-like nanomaterials-integrated microfluidic technology for bioanalysis, TrAC Trends in Analytical Chemistry, 2023, 158, 116833. https://doi.org/10.1016/j.trac.2022.116833.

183. J. Qin, N. Guo, J. Yang and J. Wei, Recent advances in metal oxide nanozyme-based optical biosensors for food safety assays, Food Chemistry, 2024, 447, 139019. https://doi.org/10.1016/j.foodchem.2024.139019.

184. H. Li, Q. Lin, R. Zou, M. Zhang, X. Liu, H. Ye, C. Sun and X. Yan, A DNA tweezer-actuated nanozyme-enzyme hybrid nanoreactor for pesticide detection, Biosensors and Bioelectronics, 2025, 271, 117064. https://doi.org/10.1016/j.bios.2024.117064.

View Article Online
DOI: 10.1039/D5TA09692H

185. S. Li, C. Pang, X. Ma, Y. Zhang, Z. Xu, J. Li, M. Zhang and M. Wang, Microfluidic paper-based chip for parathion-methyl detection based on a double catalytic amplification strategy, Mikrochim Acta, 2021, 188, 438. 10.1007/s00604-021-05084-6.

186. H. Pan, W. Zhang, M. Jin, F. Zhang, X. Chen, X. Meng, H. Shao, L. Song, Z. Zhang and C. Wang, Portable SERS device for rapid detection of indoxacarb and chlorfenapyr in vegetable juice, npj Science of Food, 2025, 9, 137. 10.1038/s41538-025-00513-9.

187. N. Tabrizi, M. Ghafori-Gorab, A. Kashtiaray, M. Karimi, H. Aghamirza Moghim Aliabadi, S. Adibzadeh and A. Maleki, Application of nanozyme-based biosensors in pesticide residue detection: a review, Materials Advances, 2025, 6, 9272–9295. 10.1039/D5MA00800J.

188. B. Yin, Z. Jiang, R. Muhammad, J. Liu and J. Wang, Nanozyme-Powered Multimodal Sensing for Pesticide Detection, Foods, 2025, 14, 1957.

189. E. M. Hamed, M. M. Elsaady and S. F. Y. Li, Single-Atom Nanozymes in Analytical Chemistry: Opportunities and Challenges, Analytical Chemistry, 2025, 97, 26313–26325. 10.1021/acs.analchem.5c05006.

190. E. L. S. Wong, K. Q. Vuong and E. Chow, Nanozymes for Environmental Pollutant Monitoring and Remediation, Sensors (Basel), 2021, 21, 10.3390/s21020408.

191. K. Wan, B. Jiang, T. Tan, H. Wang and M. Liang, Surface-Mediated Production of Complexed •OH Radicals and Fe□O Species as a Mechanism for Iron Oxide Peroxidase-Like Nanozymes, Small, 2022, 18, 2204372. https://doi.org/10.1002/smll.202204372.

192. J. Li, W. Liu, X. Wu and X. Gao, Mechanism of pH-switchable peroxidase and catalase-like activities of gold, silver, platinum and palladium, Biomaterials, 2015, 48, 37–44. https://doi.org/10.1016/j.biomaterials.2015.01.012.

193. J.-F. Masson, Consideration of Sample Matrix Effects and "Biological" Noise in Optimizing the Limit of Detection of Biosensors, ACS Sensors, 2020, 5, 3290–3292. 10.1021/acssensors.0c02254.

194. X. Yu, W. Zhuang, W. Bai, Q. Li, H. Tan, L. Zhang, J. Zhang, Y. Yao, S. Li, H. Bai, J. Hu, X. Sun and W. Hu, Nanozyme-based biosensors with different combinations of sensing modes for clinical biomarker detection: Biosensing strategies, practical applications, and future perspectives, Coordination Chemistry Reviews, 2025, 542, 216850. https://doi.org/10.1016/j.ccr.2025.216850.

View Article Online
DOI: 10.1039/D5TA09692H

195. S. Wu, Z. Yu, J. Zhao, Y. Wang, J. Nan, L. Xu, X. Li, L. Yang and S. Dong, Fluorescent Nanozyme Based on Bimetallic Fe/Co-Doped Carbon Dots for Dual-Mode Detection of Ascorbic Acid and Hydrogen Peroxide, Analytical Chemistry, 2025, 97, 15320–15328. 10.1021/acs.analchem.5c02107.

196. L. Xi, Y. Chen, X. Zhang, M. Liu, J. Li, D. Xiao, P. Dramou and H. He, Less interference fluorescence analytical strategy: Bridging substance-triggered ratiometric sensor with convenient preparation and application, Talanta, 2024, 275, 126102. https://doi.org/10.1016/j.talanta.2024.126102.

197. X. Liao, X. Luo, Y. Li, Y. Zhou, Q. Liang, K. Feng, M. B. Camarada and J. Xiong, An antifouling electrochemical sensor based on multiwalled carbon nanotubes functionalized black phosphorus for highly sensitive detection of carbendazim and corresponding response mechanisms analyses, Microchemical Journal, 2023, 190, 10.1016/j.microc.2023.108671.

198. S. Wang, P. Qi, S. Di, J. Wang, S. Wu, X. Wang, Z. Wang, Q. Wang, X. Wang, C. Zhao and Q. Li, Significant role of supercritical fluid chromatography - mass spectrometry in improving the matrix effect and analytical efficiency during multi-pesticides residue analysis of complex chrysanthemum samples, Anal Chim Acta, 2019, 1074, 108–116. 10.1016/j.aca.2019.04.063.

199. Z. Kramplová, A. Ferancová, T. Maliar and A. Purdešová, Tuneable properties of boron-doped diamond working electrodes and their advantages for the detection of pesticides, Journal of Electroanalytical Chemistry, 2023, 949, 10.1016/j.jelechem.2023.117846.

200. Y. Li, R. Han, X. Yu, L. Jiang and X. Luo, A low-fouling electrochemical biosensor based on multifunction branched peptides with antifouling, antibacterial and recognizing sequences for protein detection in saliva, Sensors and Actuators B: Chemical, 2024, 405, 10.1016/j.snb.2024.135322.

201. Y. Li, X. Pu, Y. Ding, L. Yi, Y. Yang, Y. Gu and S. Wang, An antifouling electrochemical sensor based on a U-shaped four-in-one peptide and poly(3,4-ethylenedioxythiophene) for vancomycin detection in fresh goat milk, Food Chem, 2025, 463, 141056. 10.1016/j.foodchem.2024.141056.

202. N. Hui, X. Sun, S. Niu and X. Luo, PEGylated Polyaniline Nanofibers: Antifouling and Conducting Biomaterial for Electrochemical DNA Sensing, ACS Appl Mater Interfaces, 2017, 9, 2914–2923. 10.1021/acsami.6b11682.

203. E. Jarosinska, Z. Zambrowska and E. Witkowska Nery, Methods of Protection of

View Article Online
DOI: 10.1039/D5TA09692H

Electrochemical Sensors against Biofouling in Cell Culture Applications, ACS Omega, 2024, 9, 4572–4580. 10.1021/acsomega.3c07660.

204. X. Ma, H. Zheng, L. Fang, H. Zhou, W. Shi and W. Zhao, Anchoring atomically distributed Mn with N, F Co-doped ultrathin carbon matrixes as multifunctional nanozymes to boost electrochemical sensing performance, Sensors and Actuators B: Chemical, 2025, 426, 10.1016/j.snb.2024.137075.

205. P. Wan, G. Chen, J. Fan, W. Tan, X. Li, L. Chen and K. Li, Modulating ion migration realizes both enhanced and long-term-stable nanozyme activity for efficient microplastic degradation, Chem Sci, 2025, 16, 15955–15963. 10.1039/d5sc04247j.

206. W. Pervaiz, M. H. Afzal, N. Feng, X. Peng and Y. Chen, Machine learning-enhanced electrochemical sensors for food safety: Applications and perspectives, Trends in Food Science & Technology, 2025, 156, 10.1016/j.tifs.2025.104872.

207. X. Wu, S. Shi, J. Jiang, D. Lin, J. Song, Z. Wang and W. Huang, Bionic Olfactory Neuron with In-Sensor Reservoir Computing for Intelligent Gas Recognition, Advanced Materials, 2025, 37, 2419159. https://doi.org/10.1002/adma.202419159.

208. Y. Chen, Y. Wu, W. Xu, Y. Tang, Y. Cai, X. Yu, J. Li, Y. Qiu, L. Hu, W. Gu and C. Zhu, Nanozyme-Based Microfluidic Chip System for pH-Regulated Pretreatment and Sensitive Sensing, Anal Chem, 2024, https://doi.org/10.1021/acs.analchem.4c0241510.1021/acs.analchem.4c02415.

209. Q. Liu, H. Wei and Y. Du, Microfluidic bioanalysis based on nanozymes, TrAC Trends in Analytical Chemistry, 2023, 158, 10.1016/j.trac.2022.116858.

210. M. Sun, S. Huang, G. Su, X. Wang, Z. Lu, Y. Wang, T. Liu, Y. Jiang, C. Song and H. Rao, Synthesis of pH-switchable Pt/Co3O4 nanoflowers: Catalytic mechanism, four-enzyme activity and smartphone biosensing applications, Chemical Engineering Journal, 2022, 437, 10.1016/j.cej.2021.134414.

211. H. Li, P. Merkl, J. Sommertune, T. Thersleff and G. A. Sotiriou, SERS Hotspot Engineering by Aerosol Self-Assembly of Plasmonic Ag Nanoaggregates with Tunable Interparticle Distance, Advanced Science, 2022, 9, 2201133. https://doi.org/10.1002/advs.202201133.

212. M. Yang, D. Chen, J. Hu, X. Zheng, Z.-J. Lin and H. Zhu, The application of coffee-ring effect in analytical chemistry, TrAC Trends in Analytical Chemistry, 2022, 157, 116752. https://doi.org/10.1016/j.trac.2022.116752.

213. T. Bhardwaj and T. K. Sharma, A perspective on the selection and design of nanozyme-based aptasensors for small molecules, Biosensors and Bioelectronics:

View Article Online
DOI: 10.1039/D5TA09692H

X, 2024, 21, 100533. https://doi.org/10.1016/j.biosx.2024.100533.

214. Q. Zhao, H. Wang, W. Jiang, H. Gao, S. Wen, X. Feng, Q. Wu, C. He, Y. Zhu, L. Hu, B. Zhao and W. Song, SERS Resolving of the Significance of Acetate on the Enhanced Catalytic Activity of Nanozymes, Analytical Chemistry, 2022, 94, 17930–17938. 10.1021/acs.analchem.2c03992.

215. G. Wang, N. Feng, S. Zhao, L. Song, Y. Zhang, J. Tong, Y. Liu, X. Kang, T. Hu, I. Ahmad Khan, K. Lu, H. Wu and J. Xie, Synthesis and DFT calculation of microbe-supported Pd nanocomposites with oxidase-like activity for sensitive detection of nitrite, Food Chemistry, 2024, 434, 137422. https://doi.org/10.1016/j.foodchem.2023.137422.

216. Y. Wang, Y. Zhao, Q. Tan, G. Xiao, J. Baeyens and H. Su, Bioinspired Bi-amino Acid Ce-MOFs Boosting Oxidase-like Activity: Dual-mode Aflatoxin Detection and Antimicrobial Activity Platform, Chemical Engineering Journal, 2025, 512, 10.1016/j.cej.2025.161977.

217. Z. Lin, G. Sun, H. Liu, X. Zhang, Z. Bian and A. Liu, Mechanism of pesticide thiram reversibly inhibiting of Pt single-atom peroxidase-mimicking nanozyme and its application in colorimetric sensing thiram, Talanta, 2025, 294, 128201. https://doi.org/10.1016/j.talanta.2025.128201.

View Article Online
DOI: 10.1039/D5TA09692H

Data Availability Statement

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.