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Review

Recent Advances in Design and Application of Nanomaterials-Based Colorimetric Biosensors for Agri-food Safety Analysis

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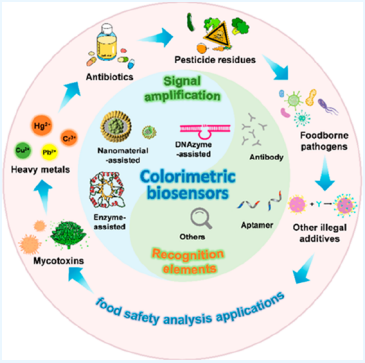
ABSTRACT: A colorimetric sensor detects an analyte by utilizing the optical properties of the sensor unit, such as absorption or reflection, to generate a structural color that serves as the output signal to detect an analyte. Detecting the refractive index of an analyte by recording the color change of the sensor structure on its surface has several advantages, including simple operation, low cost, suitability for onsite analysis, and real-time detection. Colorimetric sensors have drawn much attention owing to their rapidity, simplicity, high sensitivity and selectivity. This Review discusses the use of colorimetric sensors in the food industry, including their applications for detecting food contaminants. The Review also provides insight into the scope of future research in this area.



1. INTRODUCTION

According to a joint report released in 2019 by the Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO), around 600 million people suffer from foodborne illnesses each year as a result of consuming unsafe foods.[1] Food safety issues are a global concern and can occur at various stages in food processing, production, transportation, sale, and storage.[2] There are many methods used for food safety testing, such as gas chromatography (GC),[3] high performance liquid chromatography (HPLC),[4] mass spectrometry (MS),[5] and polymerase chain reaction (PCR).[6] The major disadvantages of above methods include complex pretreatment procedures, trained personnel, expensive instruments, and nonportability of analysis.[7,8] Nowadays, nanotechnology is rapidly developed in the food industry, especially nanosensors for agri-food safety detection. In the past decade, it has become a promising scientific field with the potential to answer the aforementioned questions. Innovation in functional materials has been driven by nanotechnology. Agriculture is the most important and stable sector of the country as it produces and provides raw materials such as food by growing plants and raising livestock.[9] Nanomaterial-based methods have gained increased attention as alternatives to traditional methods for agri-food safety analysis.[10] Biosensors are analytical devices based on receptors in detection and sensors used for response measurements, which have gained increasing attention due to their effective, sensitive, selective, fast, and low-cost benefits.[11] In particular, colorimetric biosensors are unique owing to their low cost, simplicity, rapidity, and naked-eye observation ability.[12] Various colorimetric methods have been developed for food safety or quality analysis.[13−15] Many colorimetric detection kits have been also successfully commercialized, including ELISA kits for food safety application and personal glucose meters.[16,17]

The basic principle of a colorimetric biosensor is to record the color change in the system induced by the analyte. Colorimetric biosensors have the advantage of allowing for preliminary judgments on the measured object through color changes with the naked eye.[18] Compared with other detection methods, colorimetric method has many advantages, such as low cost, simplicity, and portability.[19] The sample can be solid or opaque liquid, which is not affected by reference materials that may change over time. This method also plays an important role in the detection of some special samples (such as harmful byproducts generated in industrial production processes). For example, Thornton et al. used nanofibers for the colorimetric detection of hydrochloric acid and studied the reusability of the fibers. After the initial doping level was reduced, the detection limit remained consistent, and after 15 repetitions, complete dedoping was observed. It is expected that the detection limit will not be further reduced in additional repeated use, and it is expected to have a virtuous

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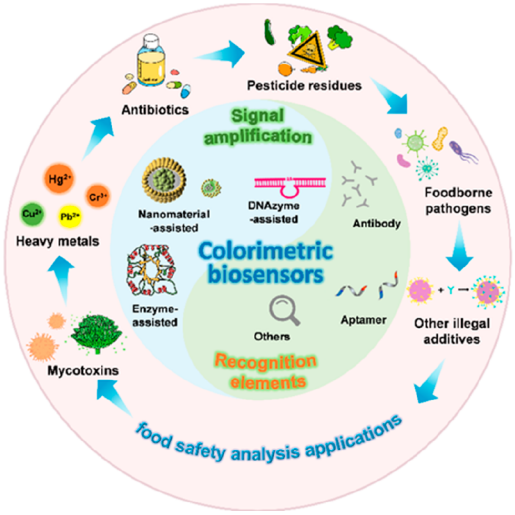
cycle in practical applications for remote detection.[20] Herein, we describe the signal amplification strategies used in colorimetric biosensors (Scheme 1). The recent developments

Scheme 1. Schematic Illustration of Nanomaterial-Based Colorimetric Biosensors for Agri-food Safety Analysis



in this area are summarized, including the colorimetric detection of mycotoxins, heavy metals, antibiotics, pesticide residues, foodborne pathogens, and other illegal additives. Finally, the challenges and perspectives of this area are presented. This study may serve as a useful reference for the rational design of nanomaterials, thereby expanding their applications in agri-food safety analysis.

2. SIGNAL AMPLIFICATION STRATEGY

2.1. DNA Amplification Methods. The introduction of signal amplification technology is indispensable for improving the sensitivity of colorimetric analysis and achieving sensitive detection. The incorporation of signal amplification technology into colorimetric biosensors has significantly promoted the development of food safety analysis techniques. These methods include nonenzymatic and enzyme-assisted amplification techniques.

Hybridization chain reaction (HCR) is an isothermal, nonenzymatic, DNA self-assembly technique for the template-free amplification of DNA sequences.[21] Specifically, the recognition of a target initiates the cross-opening of DNA hairpins, leading to the formation of polymeric DNA nanowires. In general, HCR exhibits linear growth in the presence of an initiator. Ma et al. used HCR to amplify the signal induced by the specific binding between a target and an aptamer.[22] Under optimized conditions, good analytical performance was achieved with a linear range of 0.1−750 μM. Then, the clustered regularly interspaced short palindromic repeats (CRISPR)/Cas system was used to recognize the amplified products. Finally, the target was converted to amplified fluorescent signals that can be detected by a smartphone. Moreover, nonlinear HCR systems, including branched and dendritic HCR systems, have been developed using complex monomers. Nonlinear HCR systems facilitate the formation of branched DNA nanostructures to achieve sensitive and selective detection.[23,24] Various complex DNA nanostructures, such as ladder- and ring-like DNA nanostructures[25] and DNA hydrogels,[26] have also been reported via the ingenious HCR.

Catalytic hairpin assembly (CHA) is an isothermal, enzyme-free amplification process for detecting multiple targets. Specifically, a pair of metastable hairpin DNA probes is

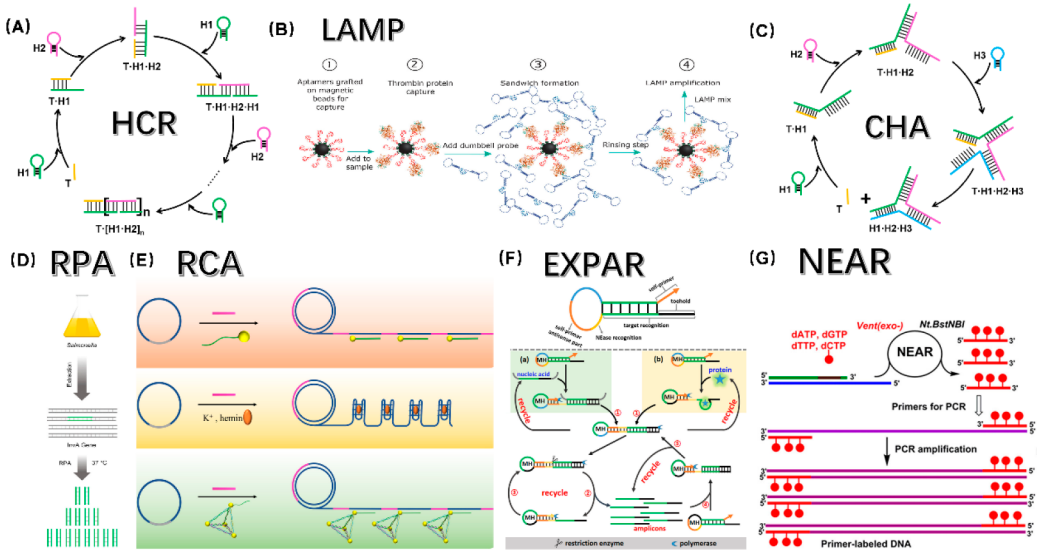


Figure 1. (A) Schematic diagram of the amplification principle of hybridization chain reaction. (B) Thrombin capture through aptamer sandwich and isothermal dumbbell exponential amplification. Reproduced with permission from ref 31. Copyright 2022, American Chemical Society. (C) Schematic diagram of the amplification principle of catalytic hairpin assembly. (D) Principle of the RPA−PCA for *Salmonella spp*. diagnosis. Reproduced with permission from ref 35. Copyright 2021, American Chemical Society. (E) Schematic diagram and detection performance of the RCA colorimetric strategy. Reproduced with permission from ref 33. Copyright 2021, American Chemical Society. (F) Scheme of SPEXPAR for detecting single-stranded nucleic acid. Reproduced with permission from ref 37. Copyright 2021, American Chemical Society. (G) Schematic diagram of enzymatic synthesis of short base-modified oligonucleotides based on NEAR. Reproduced with permission from ref 39. Copyright 2013, American Chemical Society.

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Table 1. A Summary of Important Amplification Methods

method	enzymes	primers	temperature (°C)	reaction time (h)	initiator	refs
HCR	–	2	37	<3	DNA	22
CHA	–	≥2	37	<4	DNA	28
LAMP	DNA polymerase	4	60−75	<1	DNA	30, 31
RCA	ligase and DNA polymerase	2	60	1.5	DNA (RNA)	33
RPA	DNA polymerase and recombinase	2	37−42	0.5−1.5	DNA	35
EXPAR	DNA polymerase and NEase	0	∼60	<0.5	short DNA (RNA)	36, 39
NEAR	DNA polymerase and nicking enzyme	2	37	0.5	DNA	38, 39

activated by a single-stranded target, and a number of hybrid double strands are cyclically assembled through a toehold-mediated strand replacement reaction, thus achieving signal amplification through producing multiple outputs from a single input in a cyclic format.[27] Lv et al. established an enzyme-free double amplification method for tetracycline measurement in milk.[28] This sensor system combined DNAzyme cleavage with CHA. The addition of tetracycline caused the release of DNA1 from the aptamer-DNA1 complex because of the specific interaction between tetracycline and the aptamer. The released DNA1 then hybridized with DNA2, activating the catalytic activity of the DNAzyme. This led to the cleavage of the substrate and the generation of new single-stranded DNA, which subsequently triggered the CHA reaction between H1 and H2. Consequently, G-quadruplex-heme DNAzyme was produced as a colorimetric signal readout. Under optimal conditions, within a dynamic range from 1 pM to 10 nM, there is a linear correlation between the absorption intensity and the logarithm of tetracycline concentration. The assay presents a detection limit of 0.89 pM. This method has high selectivity for tetracycline detection in milk samples.

Loop-mediated isothermal amplification (LAMP) can amplify the signal of the input template in a short time, eliminating the need for highly complex thermal cycle equipment. All strand replacement reactions occur under isothermal conditions with simple operation, high specificity, and easy product detection.[29] To accelerate the detection process, Dangtip et al. developed a colorimetric method based on LAMP using the pH indicator xylenol orange (XO).[30] The pH range of XO is suitable for the instantaneous color change of the pH decline in positive LAMP reactions. This method reduced the time required for conventional nucleic acid amplification and downstream confirmation and could eventually be redesigned to detect other aquatic and zoonotic pathogens. Aubret et al. developed an aptasensor that incorporated the specificity of aptamers and amplification of LAMP.[31] Two types of biomarkers, a nucleic acid target and thrombin, were chosen as model analytes. First, aptamer-coated magnetic beads were used to capture the targets, leading to the formation of a sandwich complex after the addition of the second aptamer. The second aptamer was integrated into a large oligonucleotide dumbbell sequence designed for LAMP detection. After rinsing steps, isothermal dumbbell index amplification was used to detect targets with detection limits of approximately 1 pM for oligonucleotides and 100 pM for thrombin, respectively (Figure 1B). Therefore, LAMP is promising for improving the detection efficiency of trace targets.

Rolling circle amplification (RCA) is an isothermal amplification process that involves a cyclic DNA template and a DNA polymerase used to lengthen DNA strands in linear or hyperbranched modes.[32] Zhang et al. developed a dual-sensitivity smartphone colorimetric system based on an RCA coil for gathering gold tetrahedra. Initiated by complementary DNA, a large amount of ssDNA was generated, which amplified the reaction signal. Simultaneously, the gold tetrahedra gathered more gold nanoparticles (AuNPs) to amplify the signal. By selecting aptamers with strong binding affinity, this method achieved a detection limit of 0.8 pM for creatine kinase isoenzyme detection. The amplification strategy using rolling circle amplification was successfully used for the detection of creatine kinase isoenzymes, demonstrating its potential for application in food safety analysis (Figure 1E).[33]

Recombinase polymerase amplification (RPA) is an isothermal amplification method carried out at 37−42 °C, which does not require complex laboratory equipment, and is considered to be a fast and sensitive technique for target detection.[34] Li et al. established a colorimetric method for *Salmonella* measurement using RPA.[35] The minimum detection concentration for this method is 5×10^3 colony forming units/mL (cfu/mL), which is are much lower than that of ELISA ($10^5 \sim 10^7$ cfu/mL). Specifically, invA from *Salmonella* genomic DNA was isothermally amplified to generate double-stranded DNA (dsDNA) amplicons, which were directly quantified using a photosensitization colorimetric assay. This method can be used to rapidly and inexpensively detect *Salmonella spp* (Figure 1D).

Exponential amplification reaction (EXPAR) exponentially synthesizes short oligonucleotides to act as primers,[36] which is characterized by its simplicity, ultrahigh sensitivity, and short reaction time. In the EXPAR assay, a primer hybridizes with a template to generate double-stranded DNA (dsDNA), which can be extended by DNA polymerase. Subsequently, nicking enzyme cleaves the dsDNA to generate 3′-OH ends, which serve as a primer to activate the next cycle. Notably, DNA polymerases and nicking endonucleases may induce non-specific amplification, leading to false-positive results (Figure 1F).[37]

Nicking enzyme amplification reaction (NEAR) is another commonly isothermal amplification method for the short oligonucleotides, which exploits a DNA polymerase and nicking endonuclease to rapidly produce and release a desired sequence because of an insufficiently stable duplex (Figure 1G).[38,39] The sequence is then regenerated and undergoes another round of amplification, resulting in the linear amplification of short oligonucleotides. NEAR is especially suitable for point-of-care (POC) testing due to its operation at a constant temperature and avoiding specialized instrumentation.

A comparison of the different amplification methods is demonstrated in Table 1. All these methods exhibit high amplification efficiency; however, they are still being optimized for practical applications.

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2.2. Enzyme-Assisted Amplification Strategy. DNAzymes are single-stranded DNA catalysts that catalyze various reactions, including the cleavage and ligation of both RNA and DNA.[40] DNAzymes consist of binding and catalytic sites.[41] Owing to their excellent properties, DNAzymes have a wide range of analytical applications due to their high stability, low cost, and easy preparation. For example, Pan et al. proposed a versatile biosensor for mycotoxin assays based on CHA and DNAzyme-cascaded hydrolysis reaction.[42] The addition of mycotoxin induced the release of trigger DNA from the aptamer-trigger DNA duplex. The trigger DNA then initiated the CHA, yielding abundant partial duplexes with toeholds, which were used for the assembly of DNAzyme-cascaded hydrolysis reactions. In the presence of Mg^{2+}, the substrate strand was cleaved into two fragments, accompanied by a fluorescence signal change for detection.

Nanozymes are artificial nanomaterial-based enzymes.[43] Nanozymes are widely used for signal amplification in biosensors because they effectively mimic the catalytic sites of natural enzymes. Based on the inhibitory effect of glyphosate on the peroxidase-like activity of porous Co_3O_4 nanoplates, Luo et al. developed a nanozyme for the colorimetric detection of glyphosate.[44] Qualitative detection of glyphosate was achieved by observing the color change of the nanozyme-based system. Similarly, Wu et al. proposed a MnO_2 nanozyme-mediated CRISPR-Cas12a system for SARS-CoV-2 detection.[45] MnO_2 nanorods linked to magnetic beads via an ssDNA linker were used as oxidase-mimicking nanozymes. Color variation occurred when Cas12a was activated by SARS-CoV-2 and indiscriminately cleaved the ssDNA linker.

Natural enzymes, such as horseradish peroxidase (HRP),[46] alkaline phosphatase (ALP),[47] acetylcholinesterase (AChE),[48] glucose oxidase (GOx),[49] superoxide dismutase (SOD),[50] and laccase[51] have also been used for signal amplification. Wang et al. prepared a mesoporous core−shell palladium@platinum (Pd@Pt) nanozyme and Pd@Pt-HRP complex (HRP coupled with Pd@Pt nanozymes) as signal amplifiers in a *Staphylococcus aureus* colorimetric immunoassay.[52] Consequently, the Pd@Pt-HRP probe exhibited remarkable peroxidase-like catalytic activity, leading to high sensitivity. Due to the expansion of publications, this Review only outlines representative examples.

2.3. Nanomaterial-Assisted Amplification Strategy. Nanomaterials, including various nanostructured materials, have been widely used to develop biosensors.[53] The introduction of nanomaterials into biosensors can amplify signals, thereby overcoming the limitations of classical analytical methods and meeting the need to detect trace amounts of various analytes.[54]

Carbon-based nanomaterials are one of the most representative materials, including carbon nanotubes (CNTs), graphene oxide (GO), and carbon quantum dots (CQDs) CNTs are graphite sheets composed of numerous carbon atoms. Owing to their unique structural characteristics, they have a high surface area and aspect ratio and are ideal carriers for multiple labels.[55] Wang et al. synthesized a composite material composed of $ZnFe_2O_4$ nanomaterials, CNTs, and glucose oxidase, which was used for glucose detection.[56] After addition, glucose was oxidized by glucose oxidase, and the intermediate product H_2O_2 further oxidized the substrate of 3,3′,5,5′-tetramethylbenzidine (TMB) to form a blue product. Graphene is a single-carbon layer of graphite with a simple atomic structure, and GO is a commonly studied derivative of graphene that contains oxygen functional groups on its surface.[57] Li et al. developed a novel GO composite probe for multistage signal amplification to improve detection sensitivity.[58] The GO composite probe was constructed through layer-by-layer assembly and integrated into an indirect competitive ELISA. The detection limit was 0.02 ng/mL for okadaic acid, which was 100-fold lower than that of conventional iELISA. CQDs are a class of carbon nanomaterials with advantages such as low toxicity, environmental protection, low cost, light stability, good charge transfer, and enhanced electronic conductivity.[59] Yue et al. designed a two-component colorimetric probe based on CQDs and *o*-phenylenediamine for the detection of Cu^{2+}.[60] The photoelectrons generated by the CQDs were captured by the oxygen solution, leading to the generation of superoxide free radicals. The colorless *o*-phenylenediamine was oxidized by superoxide free radicals to form yellow oxidation products. This sensor system was applied to analyze Cu^{2+} in seawater and tap water samples and achieved satisfactory results.

Metal nanoparticles, especially AuNPs and AgNPs, are widely used in colorimetric biosensors.[61] Jabariyan et al. used grape juice to prepare AgNPs and applied them to the colorimetric detection of Cd^{2+}.[62] Owing to the strong coordination interaction between Cd^{2+} and the peptide bonds or hydroxyl groups of the compounds in grape juice, AgNPs was easily aggregated after the addition of Cd^{2+}, resulting in color changes in the solution. Yu et al. proposed a colorimetric biosensor based on the Mn^{2+}-mediated aggregation of AuNPs for the fumonisin B1 assay.[63] Following hydrolysis of ascorbic acid 2-phosphate (AAP), the resulting ascorbic acid (AA) caused the MnO_2 shell to decompose, releasing Mn^{2+} ions that then deposited onto the surface of AuNPs, leading to their aggregation. The color change induced by the aggregation of AuNPs could be detected using a smartphone.

Hybrid nanostructures have been successfully used to produce many hybrid nanoparticles using innovative nanocomposite technologies and advanced surface passivation methods. Owing to their color adjustability and light resistance, hybrid nanostructures have demonstrated significant performance improvements in various applications.[64] Malahom et al. successfully developed a sensitive paper-based CN-selective test kit using catalytic colorimetry for Ag_3PO_4/Ag nanocomposites.[65] The composite instantly oxidized the color-developing substrate under acidic conditions. Cyanide gas was complexed with the covalent bond of Ag^+, which changed the color intensity of the detection area without H_2O_2. The color intensity of the paper-based test kit decreased with increasing cyanide concentration, and this test kit was successfully applied to real food samples, such as fruit juice. Facure et al. established a fast and sensitive food antioxidant colorimetry method based on a MnO_2/graphene quantum dot (MnO_2/GQD) composite material.[66] The composite material exhibited excellent oxidase-like catalytic activity, which triggered the colorimetric reaction of TMB. The ability of antioxidants to reduce oxTMB was evaluated by the color changes during the oxidation process. This method can be used for the accurate determination and identification of antioxidants in real food samples.

Recently, emerging novel nanomaterials, such as metal−organic frameworks (MOFs),[67] nanoclusters,[68] covalent−organic frameworks,[69] and MXenes[70] have also been reported for food safety assays. Among them, MOFs with diverse

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skeleton composition, abundant organic ligands, high specific surface area and good biocompatibility have broad application prospects.[71] Ma et al. established a real-time platform for seafood freshness monitoring based on MOF and advanced computer technology.[72] The fuel monomer was loaded with a parallel template formed by chitosan and UiO-66. The sensor platform formed a gas fingerprint after detecting the gas released by the inverted shrimp, and monitored the freshness of the shrimp by recognizing the odor fingerprint of the shrimp through a high-performance computer. In another work, Zhan et al. designed a MOF skeleton-based film for the establishment of a label-free colorimetric sensor array.[73] This array can be used to identify fresh and spoiled food by reading signals from its spectrum or from photos by a smartphone camera. Lai et al. synthesized a manganese ion modified porphyrin metal−organic skeleton, which catalyzed the oxidation of TMB in the absence of hydrogen peroxide to produce blue TMB oxide, thus establishing a simple colorimetric detection method for glutathione.[74] Zhang et al. reported a switchable colorimetric probe toward fipronil residue sensitized by aptamer-catalyzed activity of affiliative ZIF-8.[75] With the help of smartphone image acquisition, fipronil-responsive discoloration degree was converted into the ratio of green and blue (G/B) with a detection limit of 0.036 μM.

3. RECOGNITION ELEMENTS

3.1. Antibodies. Immunoassays using antibodies as target recognition elements are the most widely used detection method, they are fast, easy to use, and can detect a wide range of analytes. Antibodies can also be obtained in the laboratory by injecting target molecules into animals and collecting their blood. Antibodies are commonly used in commercial bioanalytical assays. Larkin et al. reported a dual-reading AuNP-based sandwich immunoassay for detecting disease biomarkers using equipment-free colorimetry and sensitive scanning. This study was conducted to identify anthrax biomarkers.[76] AuNP-antibody conjugates were utilized as both signal transduction and amplification agents to catalyze the reduction and precipitation of platinum or gold on the surface. This led to the generation of distinct colorimetric or optical scanning signals, which were used for detection purposes. A novel sandwich pair of monoclonal antibodies for the detection of anthrax protective antigens was identified using the generated Pt colorimetric readings.

ELISA is a commonly employed technique in the food industry for detecting the presence of various target analytes. While ELISA is known for its simplicity and high sensitivity, there are certain limitations associated with this method. The most significant problem is the laborious preparation and purification of enzyme-antibody conjugates.[77] Therefore, it is necessary to develop appropriate methods to address these problems for practical applications.

3.2. Aptamers. Aptamers are single-stranded oligonucleotides with specific recognition and binding abilities toward target molecules, which can be obtained using the exponential enrichment of ligand phylogenetic evolution (SELEX) method. Aptamers have the advantages of a small molecular weight, easy modification and synthesis, and good stability.[78] In recent years, aptamers have garnered attention in the biosensor field as signal recognition elements. Aptamers have become more popular than antibodies for the molecular diagnosis of a wide range of biomarkers. They can be chemically modified or conjugated with different labels, enabling their use in building sensitive and highly selective sensors.[79]

Aptamer-based biosensors can be used to detect factors harmful to human health, and the scope of application of these methods is far greater than that of conventional methods. Therefore, various biosensors have been developed by fixing aptamers on carriers, such as QDs and AuNPs, which have distinctive characteristics.[80] Zhu et al. used boron nitride QDs to anchor porous CeO_2 nanorods with aptamers for the sensitive determination of kanamycin. The incorporation of kanamycin aptamers and boron nitride QDs led to improved dispersion and substrate affinity of the resulting boron nitride QDs/CeO_2 nanozyme. Kanamycin inhibited the catalytic activity of nanozymes via aptamer-target binding. The limit of detection for kanamycin was 4.6 pM.[81] Wang et al. established a new colorimetric aptasensor for carbendazim based on the specific binding ability of the aptamer and color change before and after the aggregation of AuNPs. The aptamer was randomly coiled in solution, combined with the AuNPs, and wrapped around the surface of the AuNPs. Upon binding to the target, the aptamer underwent a conformational change and formed a three-dimensional structure, resulting in unprotected AuNPs that readily aggregated in the presence of a salt solution, accompanied by a color change of the AuNPs after aggregation. Consequently, the limit of detection for carbendazim was 2.2 nM.[82]

The recognition ability of the aptamer toward the target can be combined into a supramolecular complex via noncovalent interactions such as hydrogen bonds, hydrophobic effects, and electrostatic interactions. These interactions can wrap a small-molecule target or insert the aptamer into a large-molecule target structure.[80] The successful screening of aptamers indicates their significant potential applications in food safety analysis.

3.3. Molecular Imprinted Polymers. Molecularly imprinted polymers (MIPs) are synthetic receptors for target molecules and are analogues of the natural antibody−antigen system.[83] Zeng et al. synthesized a molecularly imprinted polymer consisting of a copper-based metal organic skeleton (MIP/HKUST-1) on a paper carrier using the sol−gel method for the selective recognition of tetrabromobisphenol A (TBBPA).[84] The adsorbed TBBPA was degraded under the action of hydrogen peroxide. The combined action of hydrogen peroxide and HKUST-1 reduced the color of oxTMB. This strategy was used for ultrasensitive and highly selective colorimetric detection of TBBPA. In another work, Zhao et al. reported a new dual-chemosensor using MIPs for rapid detection of atrazine in apple juice.[85] MIPs can effectively extract atrazine from apple juice, and the prepared gold nanoparticles of different sizes increase with the concentration of atrazine. The color of the samples gradually changed from red to blue with a limit of detection as low as 0.0012 mg/L. This method has low cost and intuitive results judgment. In future research, strategies such as amplifying signals and reducing nontargeted adsorption should continue to be adopted.

3.4. Peptide-Based Recognition Elements. Peptides with secondary structural rigidity and recognition flexibility, are more suitable than nucleic acids as a wide range of target molecular receptors. They can interact with different binding sites on the target molecules, and there is increasing recognition of the prospect of peptides as biosensors, which can provide a high level of specificity, sensitivity, and stability

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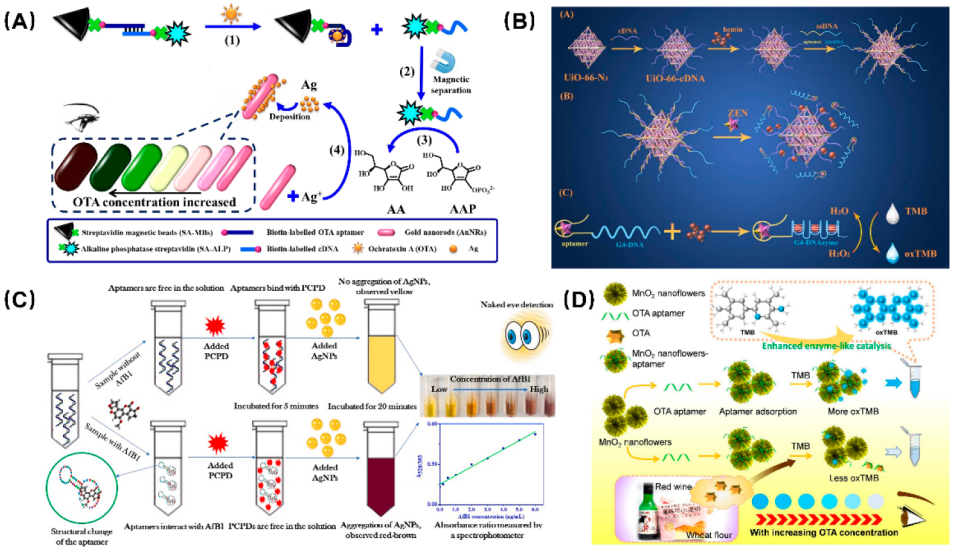

Figure 2. (A) Working principle of the multicolorimetric detection of OTA based on the structural switching of aptamer and the enzyme-induced deposition of AuNRs. Reproduced with permission from ref 106. Copyright 2020, Elsevier. (B) Synthesis of hemin-entrapped MOF gated by the duplex cDNA/ssDNA, where ssDNA includes the sequence of the ZEN aptamer and trimeric G4-DNA. Reproduced with permission from ref 103. Copyright 2022, Elsevier. (C) Schematic demonstration of AFB1 detection based on colorimetric aptasensor utilizing the specific aptamer, PCPD, and AgNPs. Reproduced with permission from ref 100. Copyright 2021, Elsevier. (D) Scheme of the colorimetric sensing platform for OTA detection using the aptamer-enhanced oxidase-like activity of MnO_2 nanoflowers. Reproduced with permission from ref 105. Copyright 2023, Elsevier.

for the detection process.[86] Wei et al. reported a colorimetric strategy for disease biomarker detection based on peptides. By introducing cucurbit[8]uril, it can selectively accommodate two *n*-terminal aromatic residues of peptides at the same time. Gold nanoparticles modified with *n*-terminal aromatic residues can form large polymers. This results in less aggregation of gold nanoparticles and enables the detection of proteins, which has also been verified in the labeled serum samples.[87] Lee et al. proposed a colorimetric strategy for rapid detection of *Aspergillus niger* based on the interaction between fungal spores and AuNPs modified with specific binding peptides. Through phage screening, the peptide ligand toward *Aspergillus niger* spore binding was identified, which showed strong affinity and specificity through polyvalent effect. Consequently, the peptide ligand was fixed on AuNPs. The method can rapidly bind the spores of *Aspergillus niger*, resulting in obvious changes in the color intensity of the supernatant after precipitation. The method can be applied to the rapid detection of relatively large size target microorganisms.[88]

3.5. Cell-Based Recognition Elements. Cell is the basic structure and functional unit of organism, cell detection or quantification is a common problem in life science research, colorimetry is one of the cell detection technologies, usually using antibodies as cell recognition elements.[89,90] The exploration of cell-based biosensors has been reported for monitoring toxic and harmful substances.[90−92]

Huang et al. constructed a DNA logic-gated module via cell-derived nanovesicles for programmable recognition capability.[93] The module is fixed on the surface of the nanovesicles, allowing the nanovesicles to perceive tumor cell targeting factors and use the signal as an input and output logic-gated. Under the guidance of the DNA logic gate, the gold carbon dots inside the encapsulated nanovesicles are delivered to the target cells. Finally, the fluorescence changes of gold carbon dots are used to reflect the changes in intracellular redox status. Similarly, Sun et al. reported a fluorescent biosensor based on 293/hTLR4A-MD2-CD14 cells for bacterial lipopolysaccharide detection.[94] This assay is carried out in a 96-well microplate which is nondestructive, user-friendly, and highly efficient. Specifically, a recombinant plasmid was transferred into 293/hTLR4A-MD2-CD14 cells through lipid-mediated, DNA-transfection way. LPS was able to bind to TLR4, and a coreceptor-induced signaling pathway could result in green fluorescent protein expression. The cells treated with LPS can be visually and continuously observed under a high content screening imaging system. The designed biosensor can detect low concentrations of LPS with a detection limit of 0.075 μg/mL.

3.6. Others. Digital colorimetry is a chemical instrumental method based on the color image processing of the analyzed sample. Molecular sensors that utilize digital colorimetry represent a promising avenue of research for identifying various substances, in addition to traditional methods such as the use of antibodies, aptamers, and DNAzymes. Monogorova et al. established an expressive qualitative and semiquantitative multisensory digital colorimetric analysis method for the raw materials of non-narcotic analgesics, which combined a molecular sensor complex with sample preparation and signal processing for the clear and usable analysis of drugs. The "barcode" multisensory digital colorimetric method can be employed for the rapid semiquantitative detection of drugs. The concentration of each active substance is used to generate a specific colorimetric code. The colorimetric code generated by this approach contains comprehensive information regarding the nature and approximate quantity of the active ingredient in the drug, using only a minimal amount of data. This makes the method both convenient and highly accurate. This method can also be assisted by using the software "barcode" scanner on a smartphone. Despite its clear advantages, digital colorimetry also has certain drawbacks, including relatively low repeatability and selectivity. Further

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Table 2. Summary of Different Colorimetric Sensors for Mycotoxins in Food Matrices

Analytes	Sample	Nanomaterials	Linear range (ng/mL)	Detection limit	refs
AFM1	milk	AuNPs	0.078−10	0.078 ng/mL	101
AFB1	peanut, animal feed	AuNPs	0.2−6.0	0.09 ng/mL	100
ZEN	maize, wheat	nanocontainer	0.01−100	0.36 pg/mL	103
OTA	wheat flour, red wine	MnO_2 nanoflowers	0.05−33.35	0.069 ng/mL	105
OTA	grape juice	AuNRs	−	9.0 nM	106

research is needed to address these issues and improve the overall performance of this approach.[95]

4. APPLICATIONS OF COLORIMETRIC BIOSENSORS FOR FOOD SAFETY ANALYSIS

4.1. Mycotoxins. Mycotoxins are secondary metabolites produced by filamentous fungi that are toxic at both acute and chronic exposure levels, interfere with nutritional processes, and may cause growth retardation in humans and livestock, seriously affecting human health.[96] Matthia et al. found that the high permeability of the blood−brain barrier to some mycotoxins (deoxynivalenol, citrinone and zearalenone) may expose the brain to high concentrations of these toxins. Other toxins can also reduce the vitality and integrity of the blood−brain barrier, which demonstrates the importance of minimizing mycotoxin contamination to reduce the risk of contact between humans and animals.[97]

Aflatoxin B1 (AFB1) is recognized as the most toxic among all the aflatoxins.[98] Both AFB1 and its main metabolite, aflatoxin M1 (AFM1), pose significant risk to human health. These toxic metabolites are present in food and feed at trace levels, highlighting the urgent need for the development of highly reliable and sensitive methods for their detection.[99] Lerdsri et al. designed a sensitive colorimetric aptasensor for the rapid quantification of AFB1. Based on the aggregation of AgNPs and local surface plasmon resonance (LSPR), the binding of the aptamer to AFB1 led to a conformational change, resulting in the dissociation of the positively charged perylene diimide (PCPD) aptamer complex, and the final release of PCPD induced AgNP aggregation. A new hue was generated for the surface plasma wavelength shift originating from the AgNPs. This method was successfully used for the detection of AFB1 in peanut, corn, and chicken feed samples (Figure 2C).[100] Liu et al. studied the use of magnetic GO combined with technology to screen a high-affinity aptamer of aflatoxin M1 (AFM1) and established an aptamer-AuNP colorimetric assay using the selected aptamer as a specific recognition probe to effectively monitor the content of AFM1 in milk.[101]

Zearalenone (ZEN) is an estrogenic mycotoxin produced by *Fusarium oxysporum* that threatens the safety of food and agricultural industries. ZEN exerts toxic effects on humans and animals through mutagenicity, teratogenicity, carcinogenicity, nephrotoxicity, immunotoxicity, and genotoxicity.[102] Sun et al. constructed an efficient aptasensor for the detection of ZEN based on stimulus-responsive functionalized MOF nanocontainers and a trivalent DNA peroxidase mimic enzyme (DNAzyme). Under the optimum conditions, the absorbance change and logarithmic concentration of ZEN exhibited a good linear range with a detection limit of 0.36 pg/mL (Figure 2B).[103] This sensor is both sensitive and economical and has the potential to be widely used in the field of food safety.

Ochratoxins are mainly produced by Aspergillus and Penicillium fungi commonly found in food, causing both economic losses and significant health risks threat to human health. Consequently, detecting ochratoxins has become increasingly important. Ochratoxin A (OTA) is the most abundant toxic ochratoxin.[104] Lv et al. proposed a colorimetric aptasensor for the detection of OTA by using the aptamer-enhanced oxidase activity of MnO_2 nanoflowers, and this sensor achieved a detection limit of 0.068 ng/mL for OTA (Figure 2D).[105] While significant progress has been made in the development of detection methods for ochratoxin A (OTA), many of these approaches are still limited by their ability to produce only a color change. As a result, these methods often suffer from poor visual resolution and have limited utility in semiquantitative analysis. To overcome this limitation, Tian et al. designed a high-resolution colorimetric method for OTA detection based on aptamer structural transformation and enzyme-induced AuNR metallization. Specifically, the aptamer bound to OTA, resulting in the formation of G-quadruplexes and the release of ALP-labeled complementary DNA (cDNA-ALP). After magnetic separation, cDNA-ALP catalyzed the reduction of Ag^+ to Ag by ascorbic acid 2-phosphate, forming an Ag shell on the AuNR surface, which caused a blue shift in the longitudinal LSPR peak of the AuNRs and a multicolor change. Under the optimal conditions, the limit of detection for OTA was 9.0 nM (Figure 2A).[106] This method is expected to be used for the on-site visual semiquantitative determination of mycotoxins in food.

A summary of the colorimetric sensors used for the detection of different mycotoxins is listed in Table 2.

4.2. Heavy Metals. The presence of heavy metals in air, water, soil, and food represents a significant threat to both human health and the environment. The prolonged half-lives of heavy metal ions can lead to their accumulation in various parts of the body and pose significant health risks.[107] Additionally, their nonbiodegradability and potential for accumulation can cause serious environmental damage, particularly when released in large quantities. Common examples of heavy metal ions include mercury (Hg), lead (Pb), and copper (Cu).

For the detection of Pb^{2+}, Huang et al. reported a rapid detection method without labeling and enzymes based on the combination of DNA enzyme-mediated RNA cleavage and DNA HCR.[108] This method is not only cost-effective and convenient to operate, but also does not require any modification of AuNPs. Moreover, it exhibits resistance to the interference of other metal ions, making it highly suitable for environmental monitoring and food safety evaluation purposes. Zeng et al. used V_6O_{13} nanoribbons as catalysts and colorimetric sensors for the simultaneous determination of Cd^{2+} and Pb^{2+} in real water samples. Cd^{2+} or Pb^{2+} can inhibit the peroxidase activity of V_6O_{13} nanoribbons and change the solution from light blue to colorless. The detection limits of the sensor for Cd^{2+} and Pb^{2+} were 1.89 μg/L and 2.11 μg/L, respectively (Figure 3A).[109]

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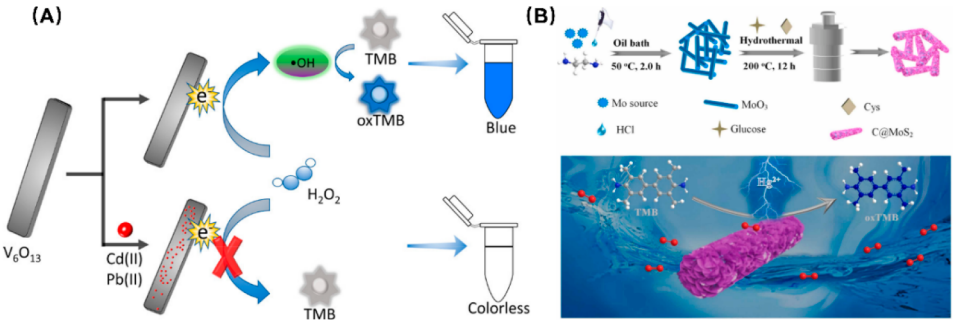

Figure 3. (A) Scheme of the colorimetric sensor based on the peroxidase-mimicking activity of V_6O_{13} nanobelts for detecting heavy metals. Reproduced with permission from ref 109. Copyright 2021, American Chemical Society. (B) Schematic illustration of the fabrication procedure of C@MoS_2 nanozyme and the principle of Hg^{2+} ions-triggered catalytic performance of C@MoS_2 nanozyme for sensing Hg^{2+} ions in catalyzing TMB reactions. Reproduced with permission from ref 110. Copyright 2022, Elsevier.

Table 3. Summary of Different Colorimetric Sensors for Heavy Metals

Analytes	Sample matrix	Nanomaterials	Linear range	Detection limit	refs
Cd^{2+}, Pb^{2+}	water	V_6O_{13} nanobelts	5−200 μg/L, 5−100 μg/L	Cd^{2+} 1.89 μg/L, Pb^{2+} 2.11 μg/L	109
Pb^{2+}	tap water	WS_2 nanowires	5−80 μg/L	4 μg/L	111
Pb^{2+}	Tap water, surface rain, pond water	AuNPs	—	2.950 nM, 5.130 nM, 10.736 nM	108
Hg^{2+}	water	C@MoS_2	0.010−100 μM	2.7 nM	110

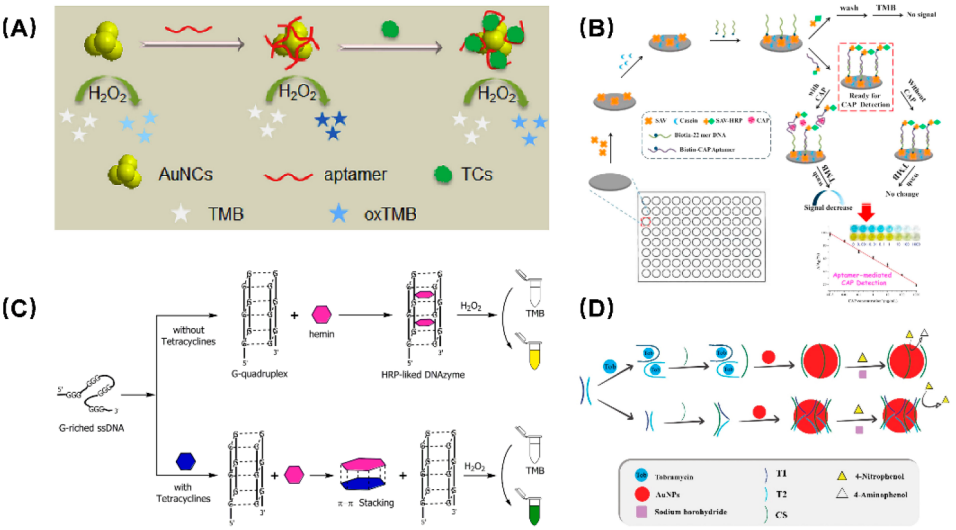

Figure 4. (A) Schematic illustration of the designed colorimetric aptasensor for TCs detection. Reproduced with permission from ref 115. Copyright 2020, Elsevier. (B) Scheme of a rapid aptamer-mediated colorimetric assay for chloramphenicol. Reproduced with permission from ref 118. Copyright 2018, Elsevier. (C) Schematic illustration of the colorimetric biosensor for tetracyclines detection using G-quadruplex DNAzyme as peroxidase mimetic. Reproduced with permission from ref 116. Copyright 2022, Elsevier. (D) Schematic illustration of the TOB detection by the three-way junction-based aptasensor and AuNPs. Reproduced with permission from ref 119. Copyright 2022, Elsevier.

Mercury is one of the most toxic heavy metals, and several methods have been developed for the detection of Hg^{2+}. However, most of them are associated with certain limitations, such as high cost, time consumption, and insensitivity. For these reasons, Feng et al. successfully synthesized C@MoS_2 with a hollow nanotube structure by the hydrothermal vulcanization of glucose using MoO_3-EDA nanowires as precursors and used Hg^{2+} to initiate the catalytic performance of C@MoS_2. Thus, a label-free colorimetric platform based on C@MoS_2 was constructed for the determination of Hg^{2+}. This platform has potential applications in environmental monitoring, biomedical sensing, and food detection (Figure 3B).[110]

A summary of the colorimetric sensors used for the detection of different heavy metals is presented in Table 3.

4.3. Antibiotics. Antibiotic residues and abuse have many adverse effects on human health, such as the transmission of antibiotic-resistant pathogens through contaminated food, immune system weakness, allergic or toxic reactions, and intestinal microflora imbalance.[112] Therefore, there is an urgent need to develop a simple and rapid technique for detecting residual antibiotics to ensure food safety.[113] Common antibiotics include tetracyclines (TCSs), chloramphenicol (CAP), and tobramycin (TOB).

TCSs are typical low-molecular-weight antibiotics widely used for the prevention and treatment of diseases.[114] Zhang et al. used a TCS-specific aptamer, gold nanoclusters, and the hydrogen peroxidase substrate 3,3′,5,5′-tetramethylbenzidine (TMB) to establish a TCS colorimetric sensor platform for use in drugs and milk. Simultaneously, a novel colorimetric sensor

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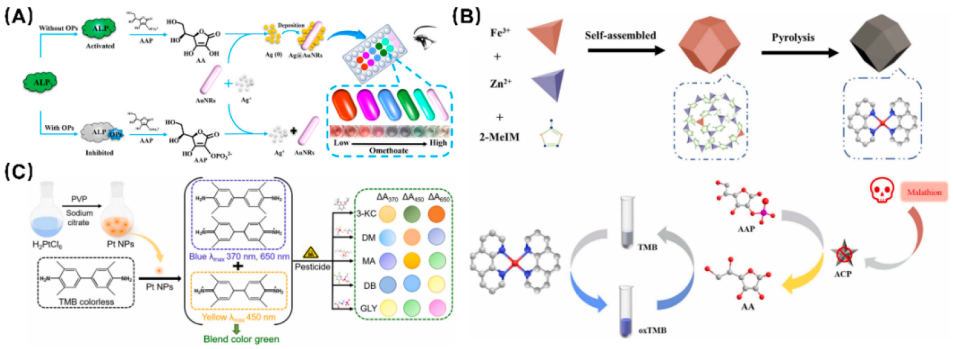

Figure 5. (A) Principle of Multicolor Colorimetric Determination of Omethoate Based on Inhibition of ALP-Induced Silver Metallization of AuNRs. Reproduced with permission from ref 126. Copyright 2020, American Chemical Society. (B) Scheme of colorimetric sensing platform for malathion assay based on Fe−N/C SAzyme. Reproduced with permission from ref 125. Copyright 2022, Elsevier. (C) Schematically illustration for construction of TMB-PtNPs multichannel colorimetric sensor array. Reproduced with permission from ref 127. Copyright 2022, Elsevier.

was constructed by combining the excellent properties of the TCS aptamer with the peroxidase activity of glutathione-stabilized gold nanoclusters (GSH-AuNCs) to detect TCS with high specificity and sensitivity. This sensor platform successfully detected TCS in drugs and milk (Figure 4A).[115] Tang et al. first proposed a colorimetric biosensor based on a G-four-stranded DNA enzyme for the detection of tetracycline antibiotics such as tetracycline, oxytetracycline, aureomycin, and doxycycline (Figure 4C).[116] Due to the abuse of antibiotics in the cattle industry, resulting in milk pollution and affecting the dairy industry and human health, Diaz et al. studied the colorimetric detection of kanamycin, oxytetracycline, sulfamethoxine, and ampicillin in raw milk by aptamer-conjugated AuNPs.[117] This method has the potential to be applied for the semiquantitative analysis of antibiotic residues in raw milk.

CAP is another a common antibiotic that threatens human health. Yan et al. developed an aptamer-mediated colorimetric assay for CAP detection. Specifically, horseradish peroxidase (HRP) was covalently linked to the aptamer through the biotin−streptavidin system to generate signals, and CAP preferentially bound to the aptamer.[118] This assay has been used to detect CAP in food samples and successfully applied to labeled food samples (honey and fish) (Figure 4B).

TOB is an aminoglycoside antibiotic with anti-infective properties, however, high levels remain in the human body, posing a serious threat to human health, including neuromuscular block, allergic reactions, and nephron toxicity. Tavakoli et al. controlled the catalytic activity of AuNPs using three-way connecting pockets. In the absence of TOB, the AuNP surface was covered by three-way connecting pockets, which prevented their catalytic activity in the reduction of 4-nitrophenol in the presence of $NaBH_4$. In the presence of TOB, the formation of a pocket was prevented, which facilitated the access of 4-nitrophenol to the AuNP surface. The catalytic reduction of 4-nitrophenol led to the color of the solution changing from yellow to colorless. This method exhibited good selectivity and has been successfully applied for the quantitative determination of TOB in human serum and milk (Figure 4D). The detection limits of this method were 1.38 μM and 1.42 μM, respectively.[119]

4.4. Pesticide Residues. Food safety is facing increasing challenges from the high concentrations of pesticide residues in fresh agriculture products, which pose a major threat to food safety. Although pesticides can prevent plants from being attacked by pests, pesticide abuse results in uncontrolled levels of residues and metabolites in the environment. Pesticides are found in grains, vegetables, beer, and other contaminated foods as well as water. Human intake of pollutants can cause headaches, vomiting, itching, skin irritation, dyspnea, and other symptoms. Because pesticide testing can eliminate substandard products and ensure food safety,[2] monitoring pesticide residues in food is very important.[120]

Carbaryl is an effective, long-residual, and broad-spectrum carbamate insecticide.[121] Deng et al. developed a polychromatic colorimetric sensor based on zinc (4-pyridinyl)-porphyrin−dodecyl trimethylammonium bromide (ZnTPyP-DTAB) peroxidase activity and gold nanodouble-pyramid etching to detect carbaryls.[122] The coordination interaction between zinc and nitrogen in the porphyrins was affected by the steric effects of the carbaryl group, which decreased the catalytic activity of ZnTPyP-DTAB. The detection limit for carbaryl was 0.26 mg/kg.

Organophosphorus pesticides (OPs) exhibit high insecticidal activity and are widely used to control pests and improve agricultural production efficiency.[123,124] Malathion is a broad-spectrum organophosphoryl pesticide marketed around the world.[124] Ge et al. designed a new, highly sensitive colorimetric platform based on an Fe−N/C single-atom nanozyme. The synthesized nanozyme directly oxidized TMB into blue products (Figure 5B).[125] Malathion can inhibit the activity of acid phosphatase, accompanied by recovery of the catalytic activity of the nanozyme. Consequently, this colorimetric assay achieved a detection limit of 0.42 nM for malathion detection.

Omethoate is another highly toxic organophosphorus pesticide. Zhang et al. designed an ultrasensitive multicolor colorimetric sensor for omethoate detection by inhibiting the metallization of silver on the surface of AuNRs induced by alkaline phosphatase (ALP) (Figure 5A).[126] This colorimetric sensor had a high sensitivity for omethoate. Li et al. reported a multichannel colorimetric assay for differentiating different pesticides using Pt nanoparticles (PtNPs) as nanozyme sensing receptors (Figure 5C).[127] PtNPs directly catalyzed the oxidation of TMB. Different colorimetric reactions were obtained based on the inhibition or enhancement of the catalytic activity of the pesticides on PtNPs. Five pesticides, dursban, dimethoate, 3-ketocarbofuran, glyphosate, and malathion, were successfully distinguished.

4.5. Foodborne Pathogens. Foodborne diseases caused by pathogens are among the most significant public health problems worldwide. Owing to their different food compositions and processing methods, the food supply chain is very

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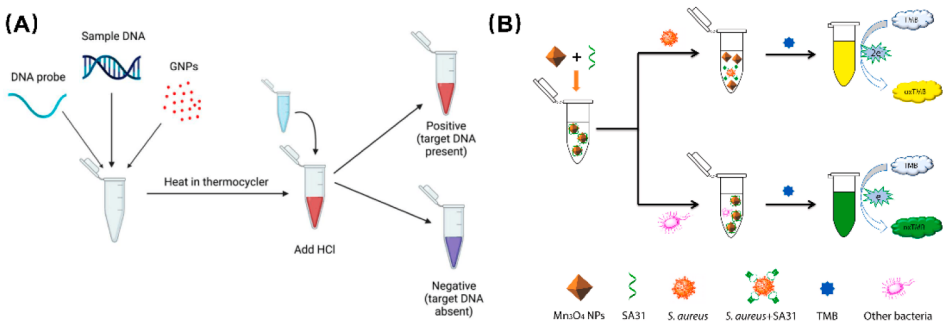

Figure 6. (A) Basic procedure for GNP boosensor. Reproduced with permission from ref 128. Copyright 2022, Molecular Diversity Preservation International. (B) Schematic of the colorimetric aptasensor for *S. aureus* detection. Reproduced with permission from ref 130. Copyright 2021, Elsevier.

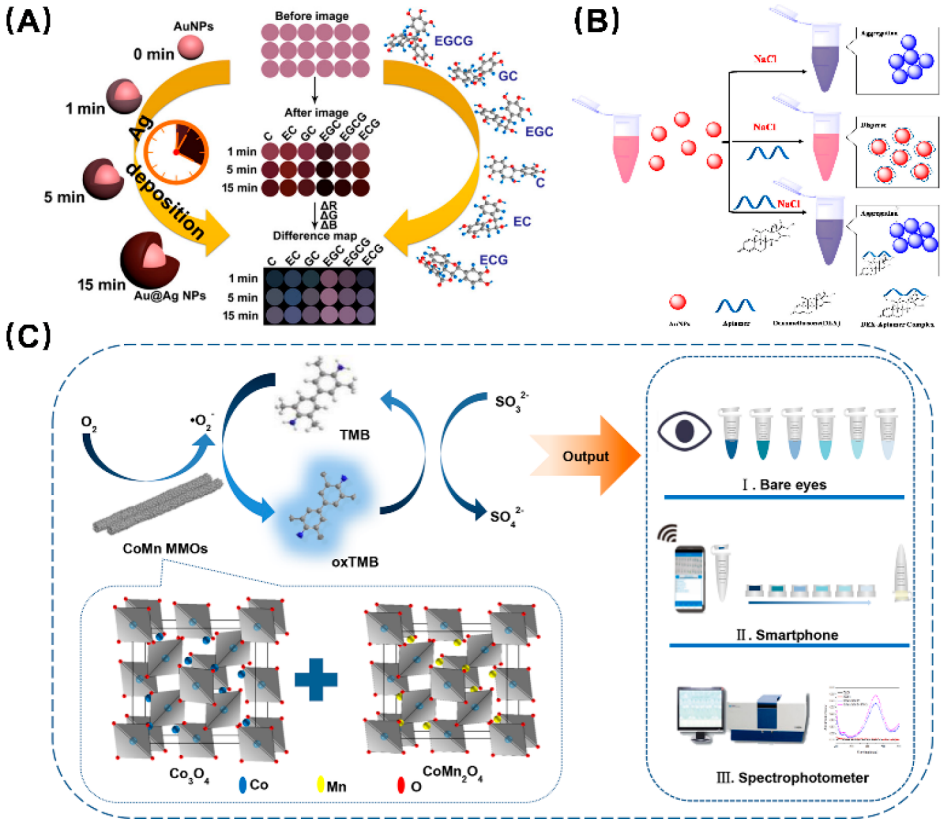

Figure 7. (A) Schematic of a colorimetric sensor array for catechin discrimination based on silver nitrate-induced metallization of gold nanoparticles at different reaction time intervals. Reproduced with permission from ref 138. Copyright 2019, American Chemical Society. (B) Schematic diagram of the colorimetric method for DEX detection based on aptamers and AuNPs. Reproduced with permission from ref 136. Copyright 2022, Molecular Diversity Preservation International. (C) A Scheme for Colorimetric Detection of SO_3^{2-} based on CoMn MMO nanorods' simulated oxidase-like activity. Reproduced with permission from ref 137. Copyright 2022, American Chemical Society.

complex, which may lead to the emergence and reappearance of foodborne pathogens. To prevent and identify health and safety problems, the detection of foodborne pathogens is important at all levels of the food production chain. Common foodborne pathogens include *Salmonella*, *Escherichia coli* (*E. coli*), and *Staphylococcus aureus* (*S. aureus*).

The rapid and portable detection of foodborne pathogens is of great significance. Dester et al. designed a colorimetric biosensor for *E. coli O157:H7* DNA detection based on AuNPs.[128] This biosensor demonstrated high specificity and sensitivity to *E. coli O157:H7* DNA at a concentration as low as 2.5 ng/μL. The test was completed within 30 min (Figure 6A).

AuNPs can be stabilized by the modification of oligonucleotides and destabilized by bacterial nucleases, which selectively cut oligonucleotide probes designed to induce the aggregation of AuNPs. A label-free colorimetric method was developed to detect nucleases secreted by Gram-positive (*S. aureus*) and Gram-negative bacteria (*Salmonella*).[129] Nucleases produced by active bacteria with aggregated AuNPs can detect bacterial pathogens using light signal sensors for zoonotic and foodborne life, providing a practical basis for the detection of nucleases in many types of food samples. This method showed sensitivity and specificity, and nuclease (1 CFU/mL) in the supernatant of bacterial cell culture was detected in less than 2 h. Based on the oxidase-mimicking activity of octahedral

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Mn_3O_4 NPs mediated by oligonucleotides, Zhu et al. established a novel unlabeled and sensitive aptasensor for the detection of S. aureus (Figure 6B).[130] Aptamers were adsorbed on the surface of octahedral Mn_3O_4 nanoparticles and inhibited enzyme activity by blocking electron transport to the TMB. Aptamers preferentially bound to bacterial cells, resulting in oxidase activity recovery. With an increase in the concentration of *S. aureus*, the color change from green to yellow was easily recognized by the naked eye. The detection limit of this method was 3 CFU/mL.

4.6. Allergen. An allergen is any antigenic substance that can mediate immediate allergic reactions and associated clinical reactions in individuals.[131] Common allergens include pollen, fungal spores, and drugs, which can enter the body through inhalation, ingestion, injection, or exposure.[132]

Chang et al. reported a sensitive colorimetric method to detect the Japanese cedar pollen allergen, Cry j 2.[133] The method coupled a CHA amplification strategy with a signal transduction based on the surface plasmon resonance of gold nanoparticles. The assay achieved a detection limit as low as 0.2 ng/mL. Moreover, the assay enables the detection of Cry j 2 spiked in soil solutions by avoiding any interference from the contaminants. The present method provides a new strategy for the development of detection methods for fungal or plant allergens. Linghu et al. developed a magnetic separation immunocolorimetric method to detect sesame allergens.[134] Sesame monoclonal antibody was modified with AuNPs as a signaling probe, and sesame allergens were attached to carboxyl functional magnetic polystyrene microspheres as a trapping probe. When sesame allergens were contained in the sample, two immune complexes would be formed. The sesame allergens in samples quantified by immune complex have been successfully detected in real samples such as bread and biscuits.

4.7. Other Illegal Additives. Common contaminants in food include not only heavy metals and mycotoxins, but also illegal additives that may be used to deceive consumers or achieve certain purposes, such as increasing the nutrient content or extending shelf life. Illegal use of food additives in animal husbandry can have serious consequences for human health. Therefore, it is important to ensure that food additives are used legally and safely. Simple on-site detection of illegal additives can help reduce the risk of fraud.[2] Common illegal food additives include dexamethasone (DEX), phosphates, tea polyphenols, and melamine.

The residues of DEX to food have been widely studied in recent decades. The long-term intake of DEX has a strong endocrine disturbance.[135] Qin et al. designed a colorimetric sensor based on unmodified aptamers and AuNPs (Figure 7B).[136] Aptamer adsorption onto AuNPs stabilized them. After the addition of DEX, the aptamer preferentially bound to DEX, inducing its desorption from the AuNPs. Upon adding salt, the AuNPs aggregated, followed by a color change of the solution. The establishment of aptasensors effectively prevents antibody screening and has significant potential for DEX determination.

Excess sulfite (SO_3^{2-}) causes serious health problems in humans, making its detection highly valuable. Zhang et al. proposed a colorimetric sensor for SO_3^{2-} based on Co−Mn mixed-metal-oxide (Co−Mn MMO) nanorods. The nanocomposite catalyzed the oxidation of the chromogenic substrate TMB to blue OXTMB. Under the optimum conditions, the linear range of SO_3^{2-} detection was 1.56−15.58 μM, and the detection limit was 62.68 nM. Combined with mobile phone chromaticity analysis, on-site semi-quantitative visual detection of SO_3^{2-} in food samples was be realized (Figure 7C).[137]

Catechin is a tea polyphenol that is the main antioxidant ingredient in green tea. However, its excessive intake is harmful to human health. Li et al. established a chrono colorimetric sensor array based on color changes caused by AuNPs at different reaction time intervals to identify catechins, in which Ag^+ was reduced to Ag by various catechins and deposited on the surface of the AuNPs. Different RGB (red, green, and blue) colors form cores at different time intervals, corresponding to certain catechins. Based on RGB fingerprints, different types of catechins were distinguished using linear discriminant analysis (Figure 7A).[138]

5. CONCLUSIONS

In summary, this review highlights various colorimetric methods and their potential applications in food analysis. Specifically, the review focuses on the detection of food contaminants using colorimetric-based sensors. Two important aspects of colorimetry are discussed, which are signal amplification technology and material identification methods. However, this method still has a long way to go before it can mature and be converted into commercial products. First, due to the wide variety and quantity of food contaminants, there are still many specific adaptors for special foods that have not been screened out. Second, the ability of adaptors to recognize targets is easily affected by environmental factors such as pH, temperature, and time, and further stability and good performance need to be given. Third, the use of nanomaterials in our daily lives is increasing, and people are also increasingly concerned about their toxicity to humans and other organisms, Liu et al. investigated carbon nanotube toxicity and found that it can affect behavior and fate in vivo, including inhalation, intravenous injection, skin or oral administration.[139] Although colorimetry is widely used for food detection, certain challenges remain.

The first challenge is the use of color rendering materials. With the promotion of green chemistry and the complexity, high cost, and environmental harm associated with traditional synthetic methods, there is an urgent need to develop environmentally friendly materials. One way is to achieve green and low-cost material synthesis. An increasing number of researchers have made progress in this regard. Another approach is to develop degradable materials that can significantly reduce environmental pollution. Therefore, colorimetric sensors are microsensors for green environmental protection, which meet the trends and needs of the future development of science, technology, and society.

The second challenge is to detect objects and ensure optimal performance. It is crucial to consider whether multiple objects can be detected simultaneously without affecting the detection performance. For instance, water samples may contain various heavy metal ions that require further investigation for their simultaneous detection.

The third challenge is the detection equipment. In general, different instruments are required for standard detection techniques, and complex sample-processing problems arise when pretreating actual samples. However, with the advancements of the digital era, rapid and accurate detection of samples can be achieved through the use of test strips or mobile phone applications.

Although colorimetry presents many challenges, it remains a classic method due to its convenience and simplicity. As

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science and technology continue to progress, it is important to strive for further advancements in detection methods to achieve more rapid, convenient, and accurate results.

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Notes

The authors declare no competing financial interest.

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