Off-On Fluorescent Nanomaterial-Based Sensors for Food Quality and Safety Assessment: Recent Advances and Future Perspectives

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ABSTRACT

Food quality and safety monitoring has become increasingly important due to the growing risk of contamination by pesticides, veterinary drug residues, pathogenic microorganisms, heavy metals, and mycotoxins. Conventional analytical methods, although highly accurate, often require expensive instrumentation, complex sample preparation, and skilled operators, limiting their application in rapid and on-site analysis. In recent years, nanomaterial-based fluorescent sensors have emerged as promising alternatives because of their high sensitivity, rapid response, portability, and low detection limits. Among them, off–on fluorescent sensors have attracted considerable attention owing to their enhanced selectivity and reduced matrix interference. These sensing platforms operate through an initial fluorescence quenching step followed by fluorescence recovery in the presence of target analytes. The sensing mechanisms are commonly based on fluorescence resonance energy transfer (FRET), photoinduced electron transfer (PET), and the inner filter effect (IFE). This review summarizes major fluorescent nanomaterials employed in off–on sensors, including quantum dots, carbon dots, and metal nanoclusters. Furthermore, key sensing strategies such as redox reactions, competitive coordination, DNA hybridization, and enzyme-mediated recognition are discussed. Recent applications in the detection of veterinary drugs, pesticide residues, foodborne pathogens, mycotoxins, and heavy metal ions are highlighted. Finally, current challenges and future perspectives for the development of portable, highly sensitive, and practical sensing platforms for food quality and safety assessment are presented.

Keywords: ***Detection Strategies; Fluorescent Nanomaterials; Food Safety; Off–On Fluorescent Sensors.***

1. INTRODUCTION

Food safety is a major global concern due to increasing contamination of food products by chemical and biological hazards, including pesticide residues, veterinary drugs, pathogenic microorganisms, heavy metals, and mycotoxins. These contaminants can accumulate in the food chain and cause severe health problems such as neurotoxicity, carcinogenicity, endocrine disruption, and immune dysfunction. Therefore, rapid and reliable detection of contaminants is essential for protecting public health and maintaining food quality standards. Conventional analytical techniques such as high-performance liquid chromatography (HPLC), gas chromatography mass spectrometry (GC–MS), atomic absorption spectroscopy (AAS), and enzyme-linked immunosorbent assays (ELISA) are widely used for food contaminant analysis. Although these methods offer high sensitivity and accuracy, they often require sophisticated instrumentation, labor-intensive sample preparation, expensive reagents, and trained personnel. These limitations reduce their suitability for rapid, real-time, and on-site

monitoring. Recent advances in nanotechnology have enabled the development of highly sensitive biosensing platforms based on fluorescent nanomaterials. Fluorescent sensors have attracted significant attention due to their simplicity, rapid response, excellent sensitivity, and non-destructive analysis. Nanomaterials such as quantum dots (QDs), carbon dots (CDs), graphene quantum dots (GQDs), and metal nanoclusters (MNCs) possess unique optical and physicochemical properties that make them excellent candidates for sensing applications. Among fluorescent sensing strategies, off–on fluorescent sensors have emerged as particularly promising platforms. Unlike conventional turn-off sensors, which rely solely on fluorescence quenching and often suffer from false-positive signals due to background interference, off–on sensors employ a dual-stage mechanism involving fluorescence quenching followed by fluorescence recovery upon target recognition. This design significantly improves selectivity, reduces background noise, and enhances analytical reliability in complex food matrices. The fluorescence switching behavior in off–on systems is typically governed by photophysical mechanisms such as fluorescence resonance energy transfer (FRET), photoinduced electron transfer (PET), and inner filter effect (IFE). Recovery of fluorescence can occur through various recognition mechanisms, including redox reactions, competitive coordination, DNA hybridization, and enzyme-mediated processes. These mechanisms enable selective detection of a broad range of analytes relevant to food safety. This review summarizes recent advances in off–on fluorescent nanomaterial-based sensors for food quality and safety assessment. Particular emphasis is placed on fluorescent nanomaterials, sensing mechanisms, detection strategies, and practical applications. Current challenges and future perspectives toward portable and intelligent sensing systems are also discussed [1-3].

2. Fluorescent Nanomaterials Used in Off–On Fluorescent Sensors

2.1 Quantum Dots (QDs)

Quantum dots are semiconductor nanocrystals typically ranging from 2–10 nm in diameter. Due to quantum confinement effects, they exhibit size-dependent fluorescence emission, high quantum yields, excellent photostability, and narrow emission spectra. These properties make QDs highly attractive for sensing applications requiring strong fluorescence signals and multiplex detection. However, the presence of toxic heavy metals such as cadmium and lead in conventional QDs raises concerns regarding environmental and food-related applications.

2.2 Carbon Dots (CDs)

Carbon dots have emerged as environmentally friendly alternatives to conventional semiconductor QDs due to their low toxicity, low cost, water solubility, and easy synthesis. Their surfaces contain abundant functional groups such as hydroxyl, carboxyl, and amino groups, facilitating chemical modification and target recognition. Although CDs generally show lower quantum yields than semiconductor QDs, heteroatom doping significantly improves their optical performance.

2.3 Metal Nanoclusters (MNCs)

Metal nanoclusters, particularly gold and silver nanoclusters, exhibit unique molecule-like fluorescence properties due to their ultrasmall size and discrete electronic states. These materials offer strong fluorescence emission, excellent photostability, and good biocompatibility. Nevertheless, structural instability and challenges in controlling particle size distribution remain major limitations [1-3].

3. Detection Strategies of Off-on Fluorescent Sensors

As illustrated in Figure 1, off–on fluorescent sensors operate through an initial fluorescence quenching step followed by fluorescence recovery in the presence of the target analyte. Compared with conventional fluorescent systems, this dual-stage sensing mechanism significantly improves selectivity, reduces matrix interference, and enhances analytical reliability in complex food samples. Fluorescence quenching in these systems is primarily achieved through photophysical mechanisms such as fluorescence resonance energy transfer (FRET), photoinduced electron transfer (PET), and the inner filter effect (IFE). In FRET, excitation energy is transferred non-radiatively from a fluorophore to an acceptor molecule, leading to reduced fluorescence intensity. In PET, electron transfer from the excited fluorophore to a quencher suppresses fluorescence emission. In IFE, spectral overlap between the absorber and fluorophore reduces the observed fluorescence signal. Fluorescence recovery and signal generation occur through different recognition strategies including redox reactions, competitive coordination, DNA hybridization, and enzyme-mediated reactions. [4-6].

3.1. Redox-Based Fluorescent Sensors

Redox reactions are among the most widely used strategies for fluorescence recovery. In these systems, oxidizing agents act as quenchers through PET, FRET, or IFE mechanisms. Upon introduction of a reducing analyte, the oxidation state of the quencher changes, reducing its quenching ability and restoring fluorescence. Ascorbic acid is one of the most commonly detected analytes using this strategy. For instance, Fe^{3+} ions can effectively quench the fluorescence of doped carbon dots, while ascorbic acid reduces Fe^{3+} to Fe^{2+}, resulting in fluorescence recovery. Similar sensing systems have been reported for dopamine detection using dichromate ions as quenchers. These sensors offer high sensitivity, rapid response, and relatively simple design. However, interference from other reducing agents present in food matrices may affect selectivity [7,8].

3.2. Competitive Coordination-Based Fluorescent Sensors

Competitive coordination is another effective off–on sensing strategy. In these systems, fluorescent nanomaterials are functionalized with amino, hydroxyl, carboxyl, or thiol groups to facilitate coordination with metal ions acting as fluorescence quenchers. Initially, coordination between the quencher and nanomaterial suppresses fluorescence. After target addition, competitive binding occurs. If the analyte has stronger affinity toward the metal ion, the quencher detaches from the nanomaterial surface, restoring fluorescence. For example, tert-butylhydroquinone (TBHQ) forms stable complexes with Fe^{3+} ions. In carbon-dot-based sensors, Fe^{3+} initially quenches fluorescence, while TBHQ removes Fe^{3+} and restores fluorescence. This strategy has also been applied to amino acids, glutathione, caffeine, and melamine detection. [9,10].

3.3. DNA Hybridization-Based Fluorescent Sensors

DNA hybridization-based sensors exploit highly specific complementary base pairing. Single-stranded DNA probes are immobilized on quenching materials such as graphene oxide or carbon nanotubes, causing fluorescence quenching through FRET. Upon addition of complementary DNA strands, hybridization forms double-stranded DNA structures with reduced affinity toward the quencher surface. Consequently, the duplex detaches, leading to fluorescence recovery. These systems have been widely used for detecting genetically modified organisms, foodborne pathogens, pesticide residues, and veterinary drugs. The incorporation of aptamers has further expanded applications to antibiotics and mycotoxins. Despite excellent specificity, high nucleic acid synthesis costs and environmental sensitivity remain limitations [11].

3.4. Enzyme-Mediated Fluorescent Sensors

Enzyme-mediated fluorescent sensors benefit from remarkable catalytic efficiency and substrate specificity. Fluorescence recovery generally occurs either through enzymatic degradation of quenching agents or through inhibition of enzyme activity by the target analyte. In the first mechanism, enzymes degrade quenchers, reducing their quenching effect and restoring fluorescence. In the second, analytes inhibit enzymatic activity. Organophosphate pesticides, for example, inhibit acetylcholinesterase, preventing the formation of fluorescence-quenching products and thereby restoring fluorescence. Although enzyme-based systems offer excellent sensitivity and selectivity, enzyme instability and production costs remain practical limitations. [12].

4. Applications of Off–On Fluorescent Sensors in Food Safety

4.1 Detection of Veterinary Drug Residues

Veterinary drug residues in animal-derived foods pose significant risks to human health, including antimicrobial resistance and toxicity. Off–on fluorescent sensors have emerged as highly sensitive analytical tools for monitoring these compounds. A sensor based on nitrogen-doped carbon dots (N-CDs) and Cu^{2+} ions was developed for enrofloxacin detection in water. The system showed a linear range of 1–15 μg mL^{-1} and a detection limit of 0.16 μg mL^{-1} [13].

4.2 Detection of Pesticide Residues

Pesticides are widely used in agriculture but may remain as residues in food products. Their accumulation can disrupt enzyme activity and cause severe toxicological effects. A fluorescence sensor based on FRET between nitrogen-doped carbon quantum dots (N-CQDs) and gold nanoclusters was developed for carbendazim detection in apples and strawberries. Aggregation of gold nanoclusters suppressed FRET and restored fluorescence. The system exhibited a linear range of 1–100 μM and a detection limit of 0.83 μM. Recent developments increasingly focus on portable sensing systems integrated with smartphones and paper-based analytical devices [14].

4.3 Detection of Foodborne Pathogenic Bacteria

Foodborne pathogenic bacteria are major causes of infectious diseases worldwide. Rapid bacterial detection is therefore essential. Antibody-conjugated quantum dots combined with graphene oxide have been used for detection of Staphylococcal infection bacteria in bread and milk samples. Specific antibody–bacteria interaction resulted in fluorescence recovery, enabling highly sensitive detection with a detection limit of 0.3 ng mL^{-1}[15].

4.4 Detection of Mycotoxins

Mycotoxins are toxic secondary metabolites produced by molds and frequently contaminate cereals, corn, wheat, and peanuts under poor storage conditions. A fluorescent sensor based on ZnCdSe quantum dots and self-assembled zinc porphyrin was developed for detection of ochratoxin A (OTA). Fluorescence quenching occurred through PET. Specific interaction between OTA and porphyrin caused separation of quantum dots and fluorescence recovery. The assay demonstrated a linear range of 0.5–80 ng mL^{-1} and a detection limit of 0.33 ng mL^{-1} in milk and coffee [16].

4.5 Detection of Heavy Metal Ions

Heavy metals are among the most hazardous contaminants in food systems due to bioaccumulation and persistence. Mercury (Hg^{2+}) and lead (Pb^{2+}) are particularly concerning because of their neurotoxicity and chronic toxicity. An aptamer-modified graphene quantum dot sensor has been reported for Pb^{2+} detection. Fluorescence was quenched by graphene oxide through PET. Binding of Pb^{2+} induced formation of a G-quadruplex structure, releasing graphene quantum dots and restoring fluorescence. The sensor achieved a linear range of 9.9–435 nM and an exceptionally low detection limit of 0.6 nM [17].

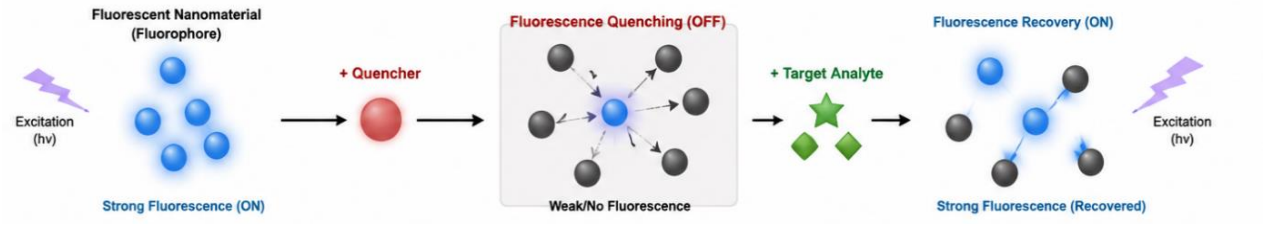


Figure 1. Schematic illustration of the general sensing mechanism of off–on fluorescent nanomaterial-based sensors[6]

5. Future Perspectives

Future research in off–on fluorescent nanosensors is expected to focus on miniaturization, automation, and intelligent sensing systems. Smartphone-assisted fluorescence readers can greatly improve point-of-care and on-site food analysis by providing portable and user-friendly platforms. Microfluidic lab-on-chip devices represent another promising direction, enabling multiplex detection of multiple contaminants simultaneously while reducing sample volume and assay time. Integration of artificial intelligence and machine learning may further improve signal processing, pattern recognition, and analyte classification in complex food matrices. In addition, the development of heavy-metal-free nanomaterials will be crucial for sustainable sensor design. Environmentally friendly fluorescent materials with high quantum yields and superior stability are expected to dominate future sensor platforms.Wearable biosensors and wireless sensing systems may also revolutionize real-time food monitoring throughout supply chains, from production to distribution and storage [6].

6.Conclusion

Recent studies have demonstrated that off–on fluorescent sensors provide excellent selectivity, broad linear response ranges, low detection limits, and strong applicability in real samples. Through integration of redox reactions, competitive coordination, DNA hybridization, and enzyme-mediated processes, these sensors enable detection of a wide range of food contaminants and quality-related compounds. Despite significant progress, several challenges remain. Signal stability and reproducibility require further improvement through nanomaterial engineering and surface modification. Some sensing systems remain relatively complex and time-consuming, highlighting the need for simplified designs and multicolor fluorescence platforms. Furthermore, many current studies remain confined to laboratory settings. The development of portable devices, paper-based platforms, smartphone-assisted systems, and field-deployable technologies will be essential for real-time and on-site applications. Future research should also expand beyond contaminant detection toward monitoring nutritional compounds, antioxidants, and phytochemicals as indicators of food quality. Continued advances in fluorescent nanomaterials and sensing strategies are expected to transform off–on fluorescent sensors into practical, intelligent, and highly efficient tools for next-generation food analysis [6].

Table 1- Representative applications of on-off-on fluorescent sensors for the detection of pesticide residues, foodborne pathogenic bacteria, mycotoxins, and heavy metal ions in food and environmental samples.

Category	Analyte	Fluorescent Nanomaterial	Quencher	Detection Strategy	Linear Range	Detection Limit	Sample Matrix	Reference
Pesticide Residues	Thiram	QDs-SiO_2NPs-CDs	AuNPs	Competitive reaction	0–10 μM	59 nM	Tap water, apple, milk	[18]
Pesticide Residues	Cartap	CDs	AuNPs	Competitive reaction	5–300 nM	3.8 nM	Tap water, cabbage	[19]
Foodborne Pathogenic Bacteria	*Pseudomonas aeruginosa*	FAM-cDNA	GOQDs	DNA hybridization reaction	$1.28 \times 10^3 - 2 \times 10^7$ CFU mL^{-1}	100 CFU mL^{-1}	Orange juice, popsicle	[20]
Foodborne Pathogenic Bacteria	*Escherichia coli* (*E. coli*)	AuNCs	Cu^{2+}	Redox reaction	10^3–10^6 CFU mL^{-1}	100 CFU mL^{-1}	Drinking water	[21]
Mycotoxins	Ochratoxin A (OTA)	Aptamer-CdTe QDs	MoS_2 nanosheets	Competitive reaction	1–1000 ng mL^{-1}	1.0 ng mL^{-1}	Red wine	[22]
Mycotoxins	Aflatoxin B_1 (AFB_1)	N-CDs	Aptamer-AuNPs	Competitive reaction	0.005–2 ng mL^{-1}	5 pg mL^{-1}	Peanut and corn	[23]
Heavy Metal Ions	Hg^{2+}	sDNA-Mn:CdS/ZnS QDs	AuNPs-sDNA	DNA hybridization reaction	0–10 nM	0.18 nM	Tap and lake water	[24]
Heavy Metal Ions	Pb^{2+}	CDs	AuNRs	Competitive reaction	0–155 μM	60 nM	Tap water	[25]

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