

Revolutionizing Food Safety: A Systematic Review of Nanotechnology-Based Aflatoxin Detection (2010–2023)

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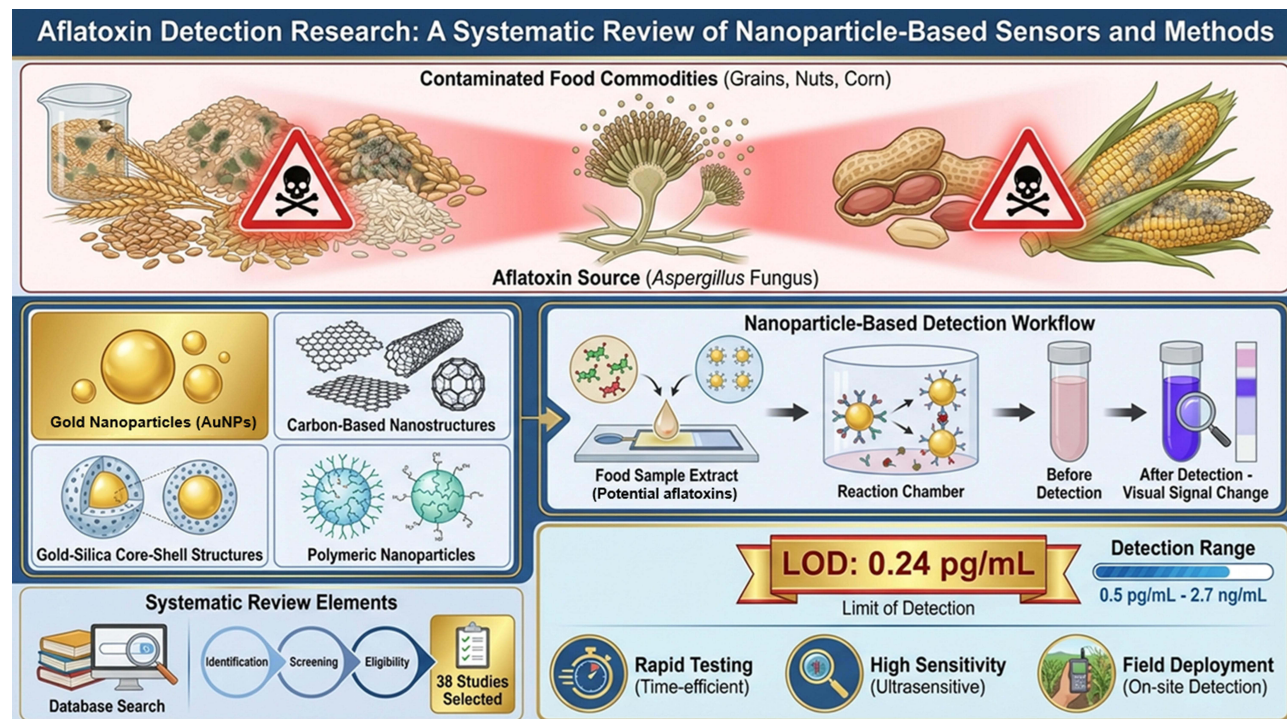
Abstract: Food safety remains a critical global challenge, particularly due to contamination by aflatoxins (AFs), highly toxic secondary metabolites produced primarily by *Aspergillus flavus* and *A. parasiticus*. This significant group of mycotoxins frequently contaminate staple food commodities, posing serious risks to public health, food security, and agricultural sustainability, thus the need for their detection in food. Conventional analytical methods, including chromatographic and immunochemical techniques, although highly accurate, are often time-consuming, resource-intensive, and dependent on sophisticated instrumentation and skilled personnel, thereby limiting their applicability in decentralized and resource-limited settings. Recent advances in detecting AFs in food matrices is nanoparticle-based, thus the focus in this systematic review. In this study, a systematic review that critically evaluates nanoparticle-based detection strategies for AFs in food, highlighting their potential to transform food safety monitoring was conducted in accordance with the Joanna Briggs Institute (JBI) guidelines. Data generated was subsequently reported following the Preferred Reporting Items for Systematic Reviews and PRISMA framework. Peer-reviewed articles published between January 1, 2010 and December 31, 2023 were systematically retrieved from multiple electronic databases. Study screening, eligibility assessment, and data extraction were independently performed using Covidence systematic review management software. A total of 38 studies met the inclusion criteria and were included in the qualitative synthesis. The findings demonstrate a strong predominance of gold nanoparticles (AuNPs), attributed to their high surface-to-volume ratio, tunable surface chemistry, and exceptional optical properties, which collectively enhance assay sensitivity and signal transduction in immunosensing platforms. Notably, gold–silica core–shell nanoparticle-based assays achieved the lowest reported limit of detection (LOD) for Aflatoxin B₁ (AFB₁) of 0.24 pg/mL. Other nanomaterials, including carbon-based nanostructures and polymeric nanoparticles, also exhibited robust analytical performance, with reported LOD ranging from 0.5 pg/mL to 2.7 ng/mL, depending on the food matrix, nanomaterial type, and assay design. Overall, this systematic review highlights key trends in nanoparticle applications for AF detection and underscores their potential for rapid, highly sensitive, and field-deployable food safety diagnostic testing. Despite substantial progress, critical challenges related to scalability, reproducibility, standardization, and regulatory approval remain. Addressing these barriers will be essential for translating nanotechnology-based AF detection platforms from laboratory research into routine food safety surveillance and regulatory practice.

Keywords: aflatoxin, nanoparticle, food safety, detection method and health risk

Introduction

Food safety remains a paramount global issue, as food products are increasingly contaminated by chemical (pesticides and heavy metals) and biological (bacteria, viruses and fungi) agents, with climate change exacerbating these risks

Graphical Abstract



posing significant health issues to both humans and animals.^{1,2} Among these contaminants are mycotoxins, a group of fungal secondary metabolites causing various adverse health effects from acute poisoning to cancer, and can even be resistant to processing like cooking.^{3,4} Hundreds of mycotoxins have been documented in food and feed, with aflatoxins (AFs) produced primarily by *Aspergillus flavus* and *A. parasiticus* being among the most significant groups of mycotoxins. This is because they are regularly detected in food and feed commodities worldwide and highly toxic, making them a global food safety issue.⁵⁻⁷ Aflatoxin B₁ (AFB₁), one main analogue of AFs is recognized as one of the most potent naturally occurring hepatocarcinogens, contributing significantly to the global burden of hepatocellular carcinoma.^{7,8} Beyond carcinogenicity, chronic exposure has been shown to impair immune function, increasing susceptibility to infectious diseases and reducing vaccine efficacy.^{8,9} Acute aflatoxicosis remains a major concern in highly exposed populations, where high-dose ingestion can result in rapid hepatic failure and high mortality rates.⁷

The socioeconomic impact of AFs is equally substantial, as contamination leads to major market and trade losses, especially in low- and middle-income countries where rejected exports and reduced commodity quality impose severe financial constraints.^{7,10} These losses directly affect household income, food availability, and the resilience of agricultural value chains.^{4,11,12} These interconnected health, economic, and food-security challenges underscore the need for more efficient, sensitive, and accessible AF detection systems capable of supporting surveillance and regulatory interventions across diverse food environments.

Conventional techniques for AF detection, including chromatographic methods such as Thin-Layer Chromatography (TLC), High-Performance Liquid Chromatography (HPLC), Liquid Chromatography–Tandem Mass Spectrometry (LC–MS/MS), and immunochemical assays like Enzyme-Linked Immunosorbent Assay (ELISA),¹³ while effective, present limitations such as high cost, complex sample preparation, use of hazardous solvents, and the need for skilled personnel, restricting their widespread application, especially in resource-limited settings.¹⁴ Moreover, the frequent contamination of agricultural products by AFs, their high toxicities in humans and animals and their adverse impacts on national and international trades, as well as the limitations of the conventional detection techniques call for highly sensitive detection methods.

Fortunately, recent advancements in nanotechnology are offering innovative solutions to these challenges. Nanoparticles, typically ranging from 1 to 100 nm in size, possess unique physicochemical properties such as high surface area-to-volume ratio, enhanced reactivity, and tunable optical and electrical features, rendering them ideal candidates for biosensing applications, including the detection of AFs in food matrices.^{15,16} For instance, electrochemical sensors based on carbon nanotubes have shown great success in accurately detecting AFs in grains and nuts.^{11,17} Interestingly, nanoparticle-based sensing platforms come with several advantages over traditional methods, including enhanced sensitivity,¹³ rapid detection,¹⁸ portability,¹⁹ and ability to detect multiple substances in a single run (Figure 1).¹⁹ For example, gold nanoparticles (AuNPs) and quantum dots (QDs) have been extensively studied for their ability to amplify detection signals in immunoassays and fluorescence-based methods.^{20,21} These advancements are paving ways for cost-effective, user-friendly point-of-care diagnostic tools, even in low-resource settings.

Over the past decade, significant progress has been attained in developing nanoparticle-based platforms for AF detection in agricultural products. Recent studies started integrating nanoparticles with advanced techniques like surface-enhanced Raman spectroscopy (SERS),²² fluorescence resonance energy transfer (FRET),²³ and microfluidics²⁴ to create highly sensitive, multiplexed detection systems. These innovations could transform food safety monitoring by enabling real-time, and high-throughput analysis. However, challenges still exist in adopting nanoparticle-based detection methods on a large scale, including issues related to scalability, cost-effectiveness, and regulatory approval. Further research is also necessary to assess the long-term stability and reliability of these sensors in real-world situations.

Therefore, this systematic review specifically focuses on recent advancements (January 1, 2010– December 31, 2023) in the use of nanoparticle-based technologies for AF detection across a variety of food matrices, including grains, nuts, dairy products, spices, and processed foods. The discussion encompasses key types of nanomaterials investigated during

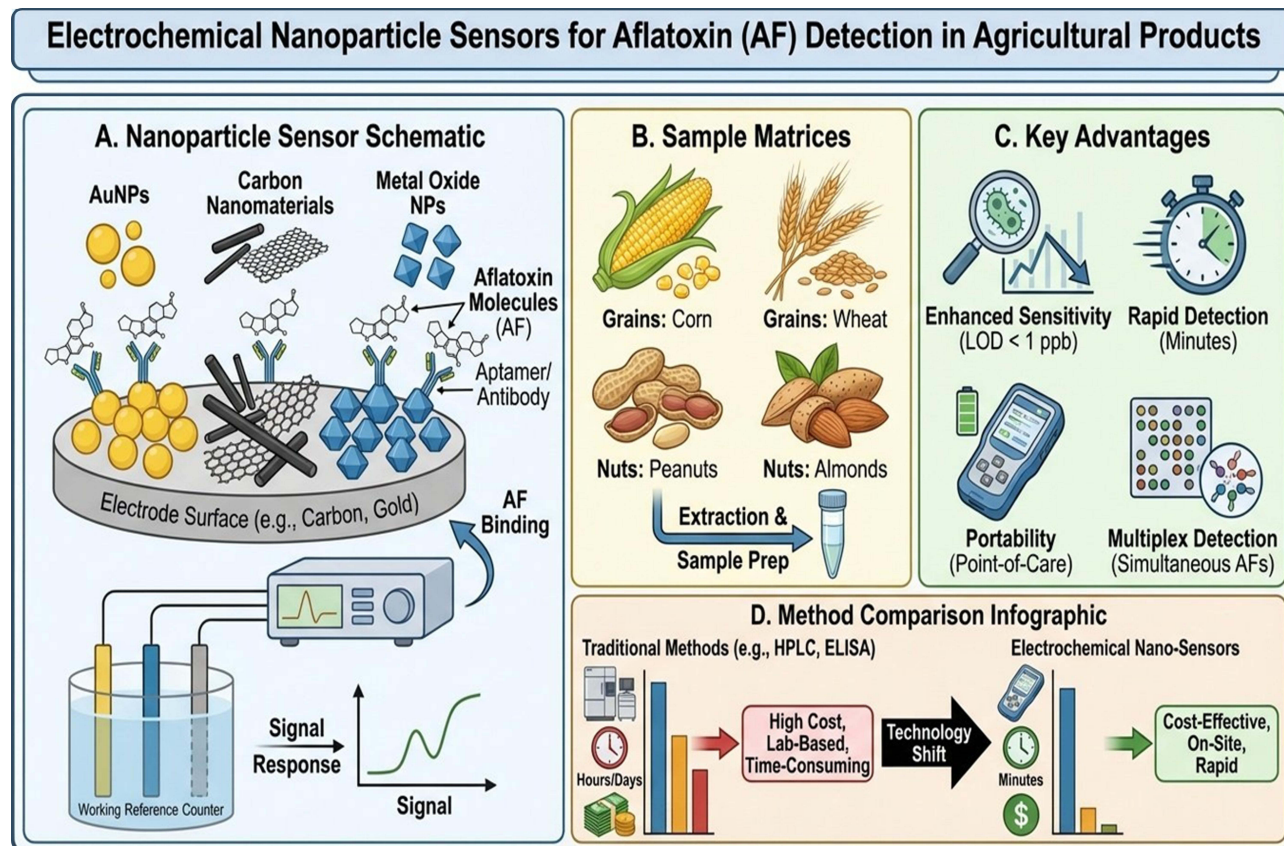


Figure 1 Nanoparticle-based electrochemical sensors for aflatoxin detection in grains and nuts. Schematic illustration showing (A) the nanoparticle-modified electrode structure and sensing mechanism for aflatoxin detection, (B) representative food matrices (grains and nuts) prone to aflatoxin contamination, (C) four key advantages of nanoparticle-based sensors: enhanced sensitivity (pg/mL to ng/mL detection limits), rapid detection (5–30 min), portability (field-deployable devices), and multiplex detection capability (simultaneous detection of multiple aflatoxin congeners), and (D) comparative performance metrics demonstrating superiority over traditional methods (HPLC, ELISA, TLC) in terms of speed, cost-effectiveness, and accessibility for point-of-care applications in resource-limited settings.

this period namely metal-based nanoparticles (such as gold, silver, and zinc oxide), carbon-based nanostructures (graphene and carbon nanotubes), and polymeric nanoparticles that have shown significant promise in improving detection sensitivity, portability, and field applicability. Also, pinpointing key research gaps, we hope to inform future research directions and contribute to innovative solutions for food safety challenges. By defining this scope, the review aims to guide readers through contemporary developments, highlight practical applications, and identify persisting challenges in translating nanotechnology-based detection systems into routine food safety monitoring. The findings from this study will be valuable for stakeholders in food science, nanotechnology, public health, and policymakers who are working to enhance global food safety standards.

Material and Methods

This systematic review was conducted in accordance with established international guidelines for systematic evidence synthesis. This review was prospectively registered in the International Prospective Register of Systematic Reviews (PROSPERO; Registration No. CRD42023478790).²⁵ No ethical approval was required, as this study synthesized data from previously published literature. Reporting of data generated followed the Preferred Reporting Items for Systematic Reviews and PRISMA 2020 statement to ensure transparency and reproducibility.^{25,26}

Study Design

This objective of this systematic review was to identify, critically evaluate, and synthesize peer-reviewed studies reporting nanoparticle-based approaches for the detection of AFs in food matrices. This was done through methodological guidance from the PRISMA Joanna Briggs Institute (JBI) throughout the review process to ensure consistency in the study selection, quality appraisal, transparency and reproducibility for the synthesis of evidence.^{26,27}

Literature Search Strategy

A comprehensive and systematic literature search was independently conducted across four major electronic databases: PubMed, Scopus, Embase, and Web of Science, in accordance with PRISMA 2020 guidelines to ensure comprehensive study identification and minimize selection bias.²⁶ These databases were selected based on their extensive coverage of biomedical, nanotechnology, and food science research. Searches were conducted for articles published between January 1, 2010 and December 30, 2023, a time-frame chosen to capture technological advances and emerging trends in nanoparticle-enabled AF detection methods (Figure 2).

Search Terms

The search strategies employed a combination of keywords and Boolean operators to ensure the inclusion of all relevant studies that met the set inclusion criteria.

The following searched keywords were used:

“Nanoparticles” OR “nanotechnology” OR “nanomaterials”

“Aflatoxin” OR “aflatoxin detection”

“Food safety” OR “food contamination” OR “food analysis” OR “food”.

Boolean Operators

The search terms were combined using “AND” and “OR” to maximize the scope:

(“Nanoparticles” OR “nanotechnology”) AND (“aflatoxin detection”) AND (“food”).

Database-specific syntax was applied where necessary to ensure optimal retrieval.

Filters Applied

Timeframe: Studies published between 1 January 2010 and 31 December 2023.

Language: Language was not a barrier.

Document Type: Original and peer-reviewed articles.

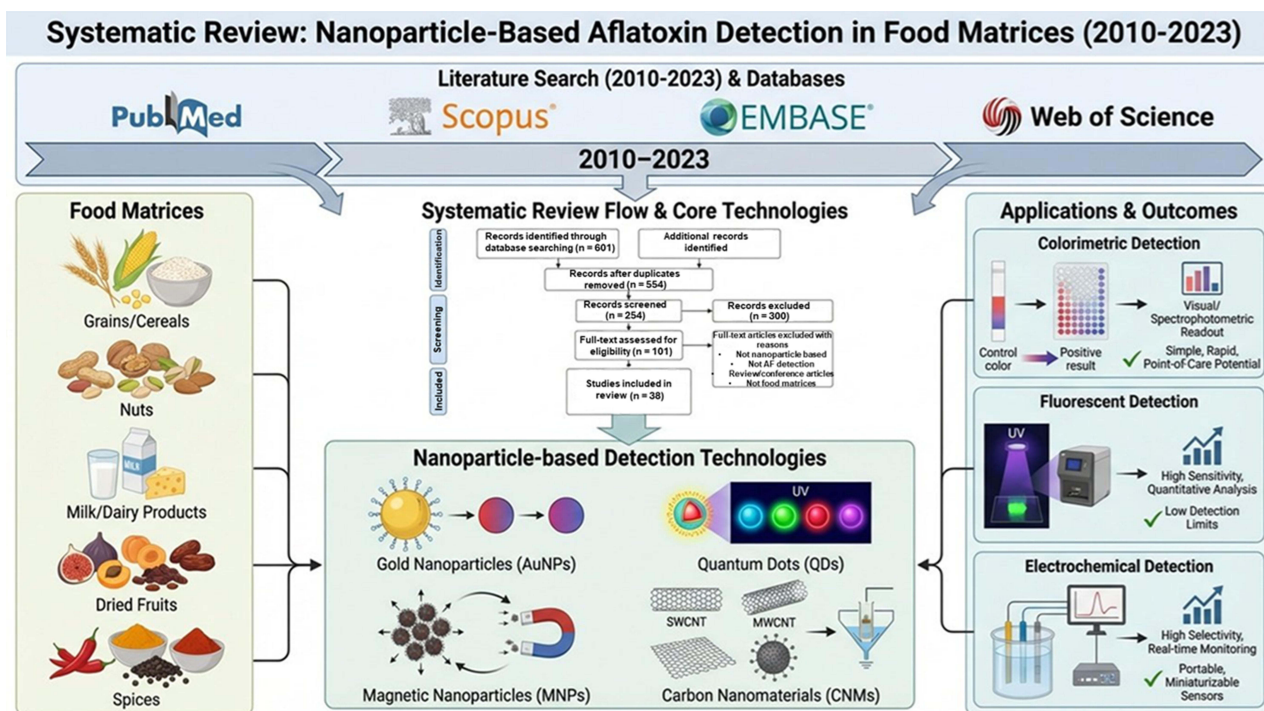


Figure 2 Schematic overview of the systematic review on nanoparticle-based aflatoxin detection in food matrices (2010–2023). Literature search strategy across major databases (PubMed, Scopus, EMBASE, and Web of Science), the PRISMA-guided screening and selection workflow, and the food matrices investigated (grains/cereals, nuts, milk/dairy products, dried fruits, and spices). It further illustrates the core nanoparticle platforms employed for aflatoxin sensing, including gold nanoparticles (AuNPs), magnetic nanoparticles (MNPs), quantum dots (QDs), and carbon nanomaterials (CNMs), and their integration into major detection modalities—colorimetric, fluorescent, and electrochemical methods—highlighting key analytical outcomes such as sensitivity, selectivity, rapid response, and point-of-care potential.

Search Queries

The search queries were tailored to the specific syntax of each database as follows:

PubMed: (Nanoparticles OR nanotechnology) AND (aflatoxin OR aflatoxin detection) AND (food safety OR food contamination OR food).

Scopus: TITLE-ABS-KEY (Nanoparticles OR nanotechnology) AND (aflatoxin OR aflatoxin detection) AND (food).

Web of Science: TS = (Nanoparticles OR nanotechnology) AND TS = (aflatoxin OR aflatoxin detection) AND TS = (food safety OR food contamination).

Inclusion and Exclusion Criteria

The inclusion and exclusion criteria were defined prior to the search to ensure the relevance and quality of the selected studies.

Inclusion Criteria

- Original, peer-reviewed experimental or analytical studies in English.
- Use of nanoparticles as a core component of AF detection.
- Application to food matrices (e.g., cereals, nuts, dairy, spices).
- Reporting of measurable analytical performance parameters (e.g., limit of detection, sensitivity, specificity).
- Publications between 2010 and 2023.

Exclusion Criteria

- Reviews, editorials, commentaries, or conference abstracts.
- Studies without nanoparticle-based detection strategies or AF detection.
- Non-food matrices (e.g., environmental or biological samples).
- Insufficient methodological detail or failure to report analytical validation parameters.
- Studies classified as low quality during critical appraisal.

Screening Process

All retrieved references were imported into Mendeley Reference Manager v2.141.0 for deduplication and subsequently uploaded to Covidence machine learning systematic review software (<https://www.covidence.org>). Title and abstract screening were carried out by independent reviewers, and articles with concordant decisions were included for further evaluation. Studies that did not fulfil the criteria were excluded at this stage.

Full texts of potentially relevant articles were retrieved and independently assessed for eligibility by the reviewers using the predefined inclusion and exclusion criteria with the aid of the Covidence software. Any discrepancies were resolved via discussion and consensus, with involvement of additional reviewers, when necessary, throughout the entire systematic review. This approach strengthens reliability and transparency and aligns best practices for high-quality systematic reviews.^{26,28} The study selection process and reasons for exclusion were documented in a PRISMA flow diagram, illustrating the number of studies retrieved, screened, excluded, and included in the final review.

Data Extraction

Data extraction was conducted using a standardized extraction form implemented in Covidence,²⁹ a widely recognized systematic review management software designed to enhance accuracy and reduce reviewer bias. Prior to the extraction process, the review team met to discuss and jointly agree on the predefined set of variables to be extracted from each eligible study, ensuring consistency and methodological transparency. Briefly, reviewers independently extracted data separately within the Covidence platform, which allows for automated tracking of disagreements and reviewer comparison.

The extracted data included the following:

Study Details: Author(s), year of publication, Nanoparticle Type: Type of nanoparticles used [eg, gold nanoparticles (AuNPs), carbon nanotubes (CNTs), quantum dots (QDs)].

Detection Method: Techniques employed (eg, electrochemical sensors, fluorescence, colorimetric detection).

Food Matrices: Type of foods analysed (eg, cereal grains, nut (with their by-products), and dairy products).

Detection Performance: Sensitivity, specificity, limit of detection (LOD), and dynamic range.

Advantages and Limitations: Key strengths and challenges of the nanoparticle-based methods.

Other Key Findings: Novel contributions or unique aspects of the study.

This dual-extraction approach minimized transcription errors and reviewer bias.

Quality Assurance in the Systematic Review

The methodological quality of included studies was assessed using a modified version of the JBI Critical Appraisal Checklist Tool³⁰ appropriate for analytical and experimental designs, with quality assurance serving as a key priority throughout the review process. Each study was independently evaluated against predefined criteria including nanoparticle characterization, validation of analytical methods, reproducibility, reporting of detection limits, and clarity of experimental design. Each criterion was scored as *yes*, *no*, *unclear*, or *not applicable*. Studies meeting $\geq 50\%$ of the applicable JBI criteria were classified as moderate to high quality and included in the synthesis. Studies scoring below this threshold were considered low quality and excluded due to insufficient methodological rigor. Each study received a quality score based on the proportion of JBI criteria met. According to the JBI scoring guidance, 16 studies (42%) were classified as low risk of bias, 17 studies (45%) as moderate risk, and 5 studies (13%) as high risk.

The methodological quality and risk of bias of all included studies were evaluated using JBI Critical Appraisal Checklists appropriate for analytical and experimental study designs. Reviewers independently appraised each study against the JBI criteria, which assess clarity of study design, adequacy of sampling and sample preparation, nanoparticle characterization, validation of analytical methods, reporting of detection limits and recovery, reproducibility of results, control of confounding factors, and transparency in methodological reporting. Inter-rater agreement between reviewers was 86%, and any discrepancies were resolved through discussion; when consensus could not be reached, an additional reviewer adjudicated the decision.

Data Synthesis

Due to substantial heterogeneity in nanoparticle types, detection principles, analytical methods, food matrices, and reporting formats, a formal statistical meta-analysis was not feasible. Accordingly, a descriptive and thematic synthesis was undertaken. Quantitative parameters such as LOD, recovery rates, and sensitivity ranges were compared narratively to identify technological trends and methodological patterns rather than statistically pooled. Furthermore, because this study is a systematic review synthesizing diverse methodological data, conventional statistical power calculations are not applicable. Instead, the rigor of the review is ensured through a comprehensive search strategy, duplicate independent screening, and structured qualitative and quantitative descriptive synthesis conducted in accordance with PRISMA and JBI guidelines.

Bias and Methodological Limitations

Potential sources of bias include selection bias and publication bias, particularly the underreporting of negative results. These risks were mitigated through independent screening, comprehensive multi-database searching, and inclusion of all eligible studies regardless of outcome direction. Nevertheless, residual bias cannot be entirely excluded and is acknowledged as a limitation of this review.

Results

A total of 601 articles were initially retrieved from PubMed ($n = 367$), Scopus ($n = 174$), Web of Science ($n = 53$), and Embase ($n = 7$). After removing 47 duplicates, 554 records remained for screening. During title and abstract screening, 300 records were excluded for not involving AF detection in food. Of the remaining 254 full-text articles, 153 were excluded because they did not apply nanomaterials in their detection methods. Further assessment led to the exclusion of 63 articles from the remaining 101 articles that did not report detection sensitivity. Ultimately, 38 studies met all inclusion criteria and were incorporated into the final qualitative synthesis as seen in Figure 3. Three (3) articles included in this study were articles published in 2011, 1 in 2013, 2 in 2014, 2 in 2015, 2 in 2018, 4 in 2019, 6 in 2020, 6 in 2021, 1 in 2022, and 11 in 2023 were considered as final extracted articles. As shown in Table 1, the most used nanoparticles include gold nanoparticles, carbon nanotubes, and quantum dots, which demonstrate significant improvement in LOD that ranged from 1.6×10^{-15} to 0.03 ng/mL.

Carbon Nanotubes (CNTs) and Multi-Walled Carbon Nanotubes (MWCNTs)

Carbon nanotubes provide a nanomaterial platform for sensitive AFs detection. Their high aspect ratio and rolled-up graphene structure give them a very large surface area, and treatments can introduce oxygen-containing groups that increase binding sites and enhance electron-transfer reactions.⁵⁵ These properties make CNTs excellent sorbents and signal amplifiers. For example, Es'haghi and colleagues³¹ fabricated a hollow-fiber solid-phase microextraction sorbent by filling a polypropylene hollow fiber with sol-gel-derived functionalized MWCNTs; when coupled with high-performance liquid chromatography–photodiode array detection, this device rapidly separated AFB₁ and AFB₂ (10-min separation) and achieved limits of detection of 0.061–0.074 µg/L, with recoveries of 47–54% in rice and 83–103% in wheat. CNTs have also been used to construct electrochemical immunosensors for AFB₁; carboxyl-functionalized MWCNTs immobilized with antibodies yielded detection limits around 0.08 ng/mL and high sensitivity because the nanotubes' conductivity and surface functional groups facilitated efficient electron transfer and analyte binding. These examples show that CNTs, with their large surface area and ability to enhance signal detection enable for rapid enrichment and ultrasensitive sensing of AFs in food matrices.

Magnetic Nanoparticles (MNPs)

Magnetic nanoparticles (MNPs) enable rapid separation and enrichment of aflatoxins and can be engineered into highly sensitive biosensors. Other approaches attach antibodies to micrometer-sized polystyrene spheres and 150 nm MNPs to concentrate the signal, allowing quantification from 0.02–200 ng/mL with a 14.3 pg/mL LOD.⁵⁶

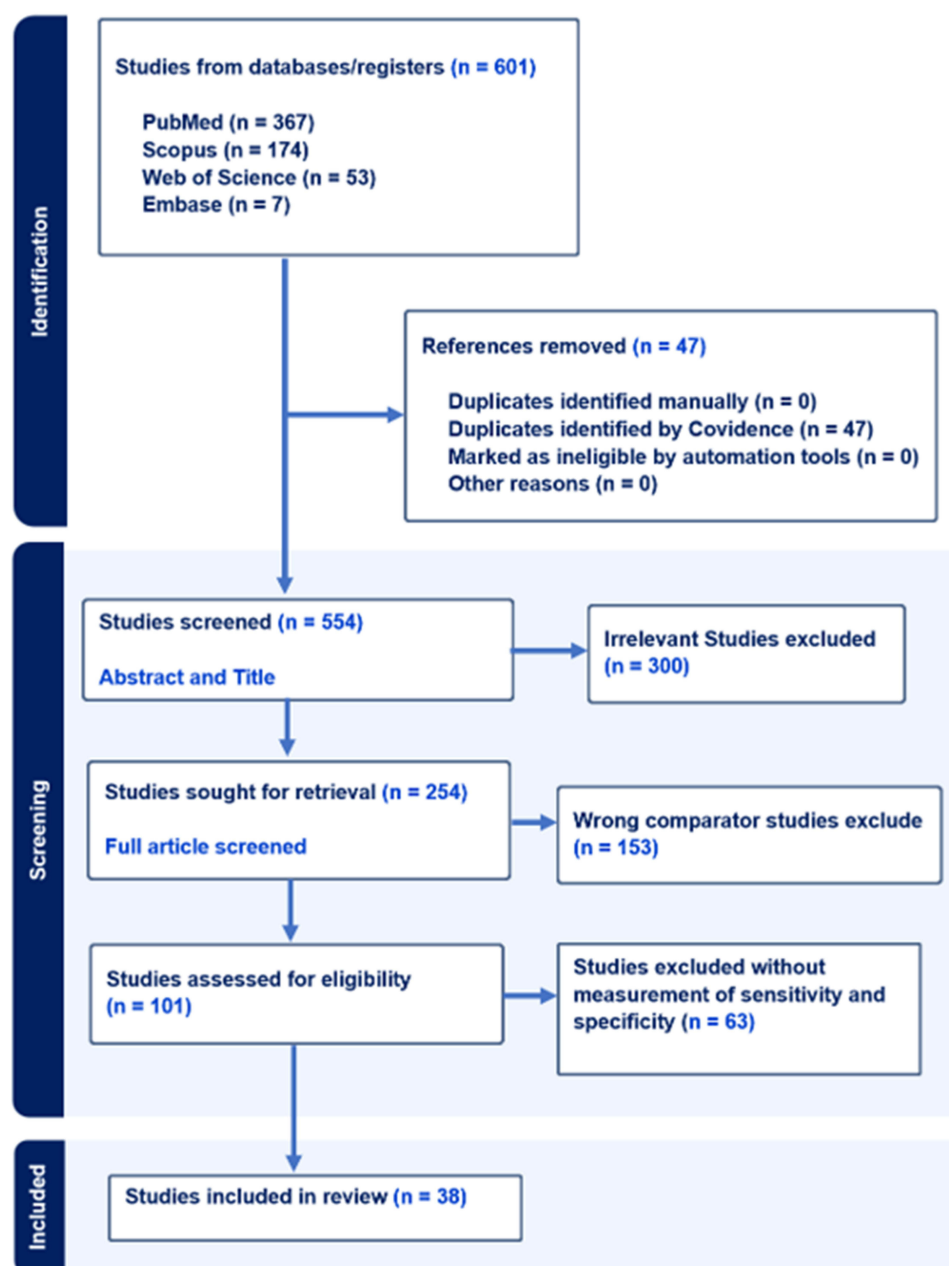


Figure 3 The flowchart summarizes the identification, screening, eligibility assessment, and inclusion of studies in this systematic review following PRISMA guidelines. A total of 601 records were identified from electronic databases (PubMed, Scopus, Web of Science, and Embase). After removal of 47 duplicate records using Covidence, 554 studies were screened based on titles and abstracts, resulting in the exclusion of 300 irrelevant studies. Full-text articles were retrieved and assessed for 254 records, of which 153 were excluded due to inappropriate comparators. A total of 101 studies underwent eligibility assessment, and 63 were excluded for lacking quantitative measures of sensitivity and specificity. Ultimately, 38 studies met the inclusion criteria and were included in the final review.

Gold Nanoparticles (AuNPs)

Often regarded as the golden standard in nanotechnology, AuNPs have become versatile tools for AFs analysis because their strong surface plasmon resonance (SPR) makes even slight changes in the local environment visible. Zhang et al⁵⁷ developed an immunochromatographic assay where monoclonal antibodies were optimally bound to AuNPs; in peanuts the test provided visual LOD of 0.03–0.25 ng/mL for AFB₁, AFB₂, AFG₁ and AFG₂ and matched HPLC measurements. Masinde et al³² subsequently constructed a portable strip in which polyclonal antibodies were immobilized on AuNPs, allowing for simultaneous quantification of AFB₁ and AFB₂ in corn and rice without sample clean-up; results were delivered in 5 min and the visual detection limit was about 0.1 ng/mL. Since then, researchers have leveraged AuNPs'

Table 1 Nanoparticle-Based Methods for Aflatoxin Detection in Food

S/N	Reference	Year	Food Matrices	Nanoparticle Type	Target	Concentration Range	Extraction Method	LOD
1	Es'haghi et al ³¹	2011	Rice, peanuts, wheat	MWCNTs	AFB ₁ , AFB ₂	Rice: 10 ng/mg; Wheat: 15 ng/mg	Methanol-water extraction, immunoaffinity cleanup	AFB ₁ : 0.074 ng/mL; AFB ₂ : 0.061 ng/mL
2	Zhang et al ³²	2011	Peanuts	Nanogold particles	AFB ₁ , B ₂ , G ₁ , G ₂	Various concentrations	Methanol-water (80:20) + 4% NaCl	AFB ₁ : 0.03 ng/mL
3	Masinde et al ³²	2013	Maize, rice	Colloidal Gold	AFB ₁ , AFB ₂	Up to 31.79 ng/g	Centrifuged/filtered extraction liquid	High cross-reactivity
4	Hashemi et al ³³	2014	Milk	Modified Fe ₃ O ₄	AFM ₁	Commercial milk samples	Centrifugation, fat removal, magnetic adsorbent	High specificity (Qualitative)
5	Urusov et al ³⁴	2014	Barley, Maize	Magnetic NPs	AFB ₁	0.02–1 ng/mL	60% methanol, 40% water, centrifugation	20 pg/mL
6	Shao et al ³⁵	2018	Maize	Quantum Dot Nanobeads (QBs)	AFB ₁ , ZEN	Real maize samples	Methanol-water (60:40), diluted with PB	High specificity
7	Gang et al ³⁶	2018	Cereals, oils	Magnetic particles (MPs)	AFB ₁	Recovery: 78%–109%	70% methanol (grains) / pet. ether (oils)	0.05 ng/mL
8	Wang et al ³⁷	2019	Peanuts	UCNPs and GNPs	AFB ₁	12.5–62.6 ng/mL	Methanol/water (6:4)	0.17 ng/mL
9	Khan et al ³⁸	2019	Maize	Gold Nanoclusters	AFB ₁	Not specified	Official methods with modifications	0.34 pg/mL
10	Ren et al ³⁹	2019	Cereal	Nanobody/ Nanoluciferase	AFB ₁	5–20 µg/kg	80% methanol-PBS, centrifugation	0.41 ng/mL
11	Ren et al ³⁹	2019	Cereal	Nanobody/ Nanoluciferase	AFB ₁	0.01–1000 ng/mL	50% methanol, filtered	5 pg/mL
12	Long Wu et al ⁴⁰	2020	Peanuts, maize, feed	m-SAP, Fe ₃ O ₄ MNPs	AFB ₁	10–100 ng/mL	Methanol-water (80:20), centrifuged	0.017 ng/mL
13	Feng et al ⁴¹	2020	Rice	BN-G/Au@Pt NRs	AFB ₁	0.0001–10 ng/mL	Methanol: water extraction	1.04 pg/mL
14	Akgönüllü et al ⁴²	2020	Maize, Peanuts	AuNPs	AFB ₁	~19.82 µg/L	60% methanol, ultrasonicated	0.5 µg/L
15	Lin et al ⁴³	2020	Peanuts	Gold Nanobipyramids	AFB ₁	Recovery: 83–125%	Methanol/water (70:30)	TRFN: 0.04 µg/kg; QB: 0.30 µg/kg
16	Xin Wang et al ⁴⁴	2020	Grains, soy, oats	TRFN, QBs, QDs	AFB ₁	0.5–10 ng/mL	Incubation and washing steps	See footnote*
17	Xu et al ⁴⁵	2021	Grain drinks	MOFs (MIL-88)	AFB ₁	1–10 µg/kg	Acetonitrile + solid-phase purification	0.028 ng/mL
18	Wu et al ⁴⁶	2021	Peanut oil, Wheat	UCNPs	AFB ₁	2.5–10 µg/kg	Methanol-water (70:30)	1 ng/mL
19	Jia et al ⁴⁷	2021	Lotus seeds	QBs	AFB ₁	Up to 12.8 ng/mL	Methanol-PBS (70:30), ultrasonic	0.0125 ng/mL

(Continued)

Table 1 (Continued).

S/N	Reference	Year	Food Matrices	Nanoparticle Type	Target	Concentration Range	Extraction Method	LOD
20	Zhao et al ⁴⁸	2021	Peanuts, maize	Fe ₂ O ₃ nanostructures	AFB ₁	Various recovery tests	Methanol-water (60:40)	9.3 pg/mL
21	Li et al ⁴⁹	2021	Feedstuffs	CdSe/ZnS QBs	AFB ₁	eg, 120 ng/mL	Methanol/acetonitrile, evaporated	0.24 pg/mL
22	Chen et al ¹⁷	2022	Maize, rice, wheat	Au@SiO ₂	AFB1	Not quantified	Methanol-water (4:1)	3.5 fg/mL
23	Wang et al ⁵⁰	2023	Maize	Perovskite QDs	AFB ₁	$5 \times 10^{-1} - 10^{-4}$ ng/mL	Methanol: water (7:3)	35.94 fg/mL
24	Dong et al ¹²	2023	Peanuts	Yolk-shell Fe ₃ O ₄	AFB ₁	1–100 ng/mL	Methanol/water (7:3)	0.03 ng/mL
25	Zhao et al ⁵¹	2023	Maize, Wine	DNA nanostructure	AFM ₁	$>1.6 \times 10^{-21}$ g/L	TCA centrifugation, immunoaffinity	1.6×10^{-21} g/L
27	Lv et al ⁵²	2023	Walnuts, food	Platinum NPs (PtNPs)	AFB ₁	0.5–250 µg/Kg	Acetonitrile: water: methanoic acid	1.145 µg/Kg
28	He et al ⁵³	2023	Rice	AgNPs@K30	AFB1	0–50 µg/kg	Acetonitrile-water, immunoaffinity	Spiked samples
29	Chen et al ⁵⁴	2023	Maize	IUCNPs	AFB ₁	Dual-channel ICA	Not specified	0.025 ng/mL

Notes: * For 16, specific LODs varied by method (MOFLISA vs ELISA).

Abbreviations: MWCNTs, Multi-walled Carbon Nanotubes; AFB1, Aflatoxin B1; AFM1, Aflatoxin M1; ZEN, Zearalenone; QBs, Quantum Nanobeads; UCNPs, Upconversion Nanoparticles; MOFs, Metal-Organic Frameworks; LOD, Limit of Detection.

optical properties to boost sensitivity; highly branched “gold nanoflowers” enhanced the brightness of lateral-flow strips and enabled a dynamic range of 0.5–25 pg/mL with a LOD of 0.32 pg/mL in rice.⁵⁸ Additionally, SPR chips coated with β -cyclodextrin-functionalized AuNPs quantitatively detected AFB₁ between 0.001 and 23.68 ng/mL with a 1 pg/mL LOD.⁵⁹ Aptamer-based sensors further expand the versatility of AuNPs: smartphone-assisted colorimetric sensors measured AFB₁ in beans within 15 min and achieved LOD ~0.08 ng/g,⁶⁰ and a dual-channel aptasensor combining magnetic AuNPs with peroxidase-like AuNP probes obtained LOD of 35 pg/mL (colorimetric) and 0.43 pg/mL (electrochemical).⁶¹ Collectively, these studies illustrate how AuNPs, whether spherical, flower-shaped or functionalized, enable rapid, equipment-free and ultrasensitive detection of aflatoxins across a range of crops and food products.

Quantum Dots (QDs)

Quantum dots (QDs) are semiconductor nanocrystals whose emission color depends on their size; they have broad excitation spectra and narrow, size tunable emission spectra, so multiple colors can be excited by a single light source, and they also show high photostability and brightness compared with traditional dyes. These optical advantages make QDs excellent fluorescent labels for aflatoxin detection. In fluorescence immunochromatography assays (QD FICA) for AFB₁ in grains, QDs provide automated detection with good sensitivity; a comparative study reported a detection limit around 0.80 μ g/kg for QD FICA, slightly higher than time resolved fluorescent nanobeads but sufficient for routine screening.⁴⁴ Wrapping thousands of QDs in silica to form quantum dot nanobeads produces highly stable probes; a multiplex immunochromatographic assay using such nanobeads simultaneously detected AFB₁ and zearalenone with detection limits of 1.65 and 59.15 pg/mL, respectively.³⁵ Thus, by exploiting tunable fluorescence, high photostability and compatibility with nanobead and electrochemical formats, QDs enable sensitive, multiplexed and rapid detection of aflatoxins in food and feed.

Upconversion Nanoparticles (UCNPs)

Upconversion nanoparticles (UCNPs) have emerged as powerful transducers for ultrasensitive AFB₁ detection in food systems due to their unique near-infrared-to-visible emission and low background interference. Wu et al⁴⁶ reported a UCNP–black-phosphorus nanosheet FRET aptasensor with a broad linear range of 0.2–500 ng/mL and a LOD of 0.028 ng/mL in food matrices. More recently, Xu and colleagues⁶² engineered a photo-activatable Fe₃O₄@nanoporous-carbon UCNP nanozyme biosensor, enabling AFB₁ detection down to 0.56 pg/mL with a working range of 0.1–10 ng/mL. In parallel, a dual-channel UCNP-based immunochromatographic strip achieved rapid on-site AFB₁ detection in maize with limits as low as 0.01–0.025 ng/mL.⁵⁴ Hua et al⁶³ and Wang et al⁶⁴ pointed out that these nanoparticles offer exceptional sensitivity, wide dynamic range, and practical applicability of UCNP-enabled sensing platforms for reliable AFs monitoring in complex food products.

Application of Analytical Techniques

The analytical methods used in these studies are impressively varied, encompassing everything from immunochromatographic assays to electrochemical detection (Figure 4). A notable trend is the growing sensitivity of these methods, which detect substances in minute quantities, sometimes as low as femtograms per millilitre (fg/mL). For instance, Chen et al⁶⁵ achieved a groundbreaking detection limit of 0.24 pg/mL for AFB₁ using gold-silica core-shell nanoparticles in a lateral flow immunoassay. Innovative techniques like SERS and FRET further showcase the advanced capabilities of these nanoparticle systems. Wu et al⁴⁰ demonstrated, new methods are consistently improving not just in sensitivity but also in specificity, enabling more accurate detection of harmful substances.

Table 1 encompasses a wide variety of food types including cereals (rice), peanuts, and milk. The recurrent focus on detecting mycotoxins, particularly AFs and zearalenone, underscores their significance as major food safety threats. Research by Li et al⁴⁹ specifically targeted AFs in various food samples. Their work illustrates how nanoparticle-based methods significantly elevate food safety monitoring. By detecting contaminants at trace levels, these technologies play a crucial role in ensuring consumer safety and adhering to regulatory standards.

Additionally, Table 2 showcases various studies conducted to identify AFs across different food matrices. This essay explores the advancements in detection methods, the intricacies of sample preparation, and the types of food tested,

Analytical Methods Used in Nanoparticle-Based Aflatoxin Detection

Integration of nanotechnology with traditional analytical techniques

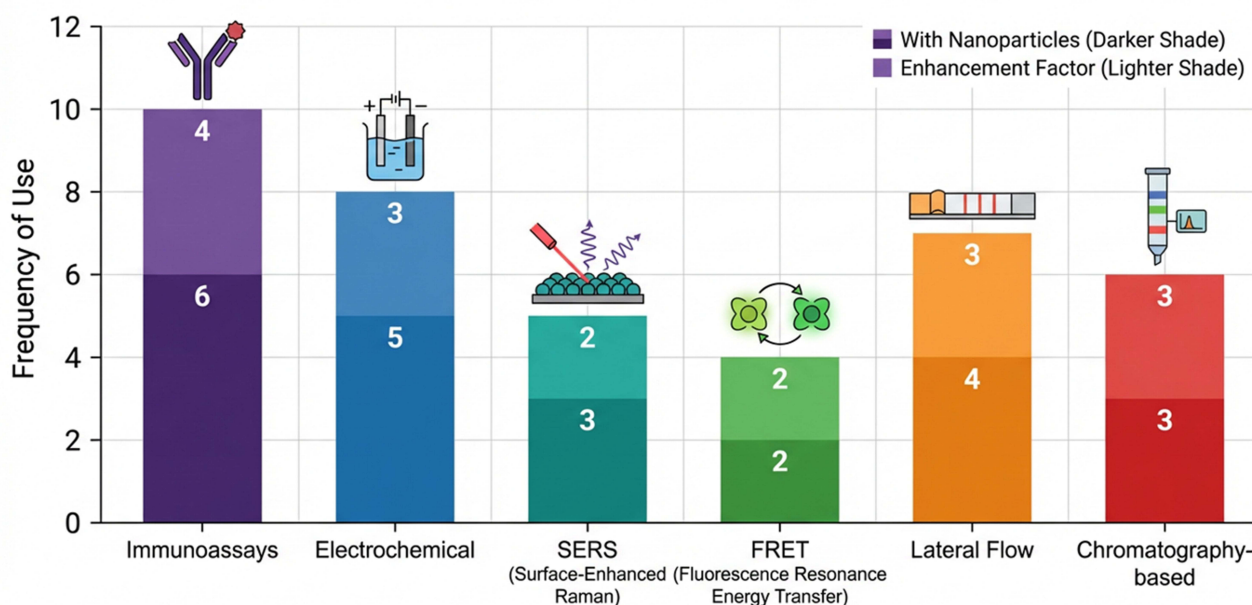


Figure 4 Frequency of analytical methods used in nanoparticle-based aflatoxin detection, highlighting the integration of nanotechnology with conventional analytical techniques. The use of major detection platforms, including immunoassays, electrochemical methods, surface-enhanced Raman spectroscopy (SERS), fluorescence resonance energy transfer (FRET), lateral flow assays, and chromatography-based approaches. Darker shades represent the number of studies employing nanoparticles directly, while lighter shades indicate the enhancement factor attributed to nanoparticle incorporation. Overall, immunoassays and electrochemical methods are most frequently combined with nanoparticles, reflecting their versatility and sensitivity gains, whereas SERS, FRET, lateral flow, and chromatography-based techniques show moderate but notable nanoparticle-driven performance enhancements.

emphasizing the continuous evolution of analytical techniques over the years. The LOD is defined as the lowest AF concentration that produces a detectable signal that is statistically different from baseline noise. Sensitivity refers to the proportion of true-positive samples correctly identified by the assay, while specificity denotes the proportion of true-negative samples accurately detected, reflecting the method's ability to avoid false-positive outcomes.

Detection Methods and Sensitivity

The detection of AFs has evolved remarkably, with increasing sensitivity and specificity in analytical methods. Early studies laid the groundwork for modern techniques, while recent advancements have pushed the boundaries of detection limits. For example, Zhang et al⁵⁷ utilized a monoclonal antibody-based approach, achieving a LODs of 0.03 ng/mL for AFB₁, which demonstrates high specificity. This method highlights the importance of using targeted approaches to detect mycotoxins in complex matrices. Such innovations indicate a trend toward using nanotechnology in analytical chemistry, improving the accuracy of AF detection.

The latest studies have reached unprecedented levels of sensitivity. For instance, the exceptionally low LOD of 1.6×10^{-21} g/L reported by Li et al⁶⁷ was achieved using an advanced immunoassay column-based detection method for AFM₁ in milk samples. Overall, the sensitivity of the included nanoparticle-based detection methods varied across studies but consistently demonstrated high analytical performance (Figure 5). Notably, Li et al⁶⁷ achieved an ultra-low LOD of 1.6×10^{-21} g/L for AFM₁, while Kim et al⁶⁸ reported an LOD of 5.0×10^{-4} pg/mL using a nano-enhanced fluorescent assay. Across the broader set of studies, LOD values generally ranged from the picogram-per-milliliter to femtogram-per-milliliter levels, reflecting the exceptional sensitivity enabled by nanomaterial-based platforms. Precision values were also robust, with most assays demonstrating intra-day and inter-day relative standard deviations (RSDs) below 10%, indicating strong repeatability and methodological reliability. Such breakthroughs are crucial for

Table 2 Nanoparticle Characterization and Detection Methods

Year	Reference	Nanoparticle Type	Size (Diameter)	Shape	Analytical Method	Detection Time	Stability
2011	Es'haghi et al ³¹	MWCNTs	Not specified	Not specified	HF-SPME + HPLC-DAD	Not specified	Stable in extraction
2011	Zhang et al ⁵⁷	Nanogold particles	Not specified	Not specified	Immunochromatography	15 min	2 months
2013	Masinde et al ³²	Colloidal Gold	20 nm	Not specified	Immunochromatographic strip	< 5 min	Stable (15–30°C)
2014	Hashemi et al ³³	Modified Fe ₃ O ₄	20 nm	Quasi-spherical	Magnetic SPE + Spectrofluorimetric	~15 min	Recoveries 91–102%
2014	Urusov et al ³⁴	Magnetic NPs	~10 nm	Spherical	ELISA	20 min	3 months
2018	Shao et al ³⁵	QBs	104 ± 14 nm	Not specified	Immunoreaction	15 min	Recoveries 81–119%
2018	Gang et al ³⁶	Magnetic particles	1.0 µm	Spherical	Chemiluminescence (MPCLIA)	Not specified	Good stability
2019	Wang et al ³⁷	UCNPs/GNPs	~43 nm/~50 nm	Spherical	SPD with LRET	Incubation steps	Excellent photostability
2019	Khan et al ³⁸	Gold Nanoclusters	~2 nm	Spherical	FRET Biosensor	30 min	High accuracy
2019	Ren et al ³⁹	Nanoluciferase	19.1 kDa	Protein	BLEIA	< 2 hours	Thermostable (55°C)
2020	Wu et al ⁴⁰	m-SAP / Fe ₃ O ₄	~190 nm (m-SiO ₂)	Spherical	NAISA	Not specified	Excellent
2020	Feng et al ⁴¹	BN-G/Au@Pt	~32 nm	Nanosheets	Electrochemical	Not specified	12 months
2020	Akgönüllü et al ⁴²	AuNPs	13.6 nm	Spherical	SPR	1 min	High (RSD <10%)
2020	Lin et al ⁶⁶	Au NBPs	70 × 22 nm	Bipyramid	SERS	25–35 min	Stable w/ binding
2020	Wang et al ³⁷	TRFN/QB/QD	90/110/15 nm	Spherical/Core-shell	FICA	Not specified	10 days (RT)
2021	Xu et al ⁴⁵	MOFs (MIL-88)	270 nm	Hexagonal prism	Fluorescence	50 min	30 days (–20°C)
2021	Wu et al ¹²	UCNPs	60.7 nm	Spherical	FRET Aptasensor	< 15 min	Stable
2021	Jia et al ⁴⁷	QBs	50–100 nm	Quasi-spherical	Lateral Flow	35 min total	High
2021	He et al ⁵³	Fe ₂ O ₃	79.5 nm	Cubic	Immunochromatography	45 min	High
2022	Li et al ⁴⁹	CdSe/ZnS QBs	84–182 nm	Spherical	FLISA	~15 min	Silica shell improves stability
2023	Chen et al ¹⁷	Au@SiO ₂	61 nm	Spherical	SERS LFA	Not specified	85% after 7 days
2023	Wang et al ⁶⁴	Perovskite QDs	5.3 nm	Cubic	ECL	Not specified	85% after 12 days
2023	Dong et al ¹²	Yolk-shell Fe ₃ O ₄	400 nm	Yolk-shell	Aptasensor	~2 hours	Good in complex matrix
2023	Zhao et al ⁵¹	DNA nanostructure	Not specified	Not specified	Fluorescent Aptasensor	Quick	2 weeks (4°C)

Comparative Detection Sensitivity of Nanoparticle-Based Methods

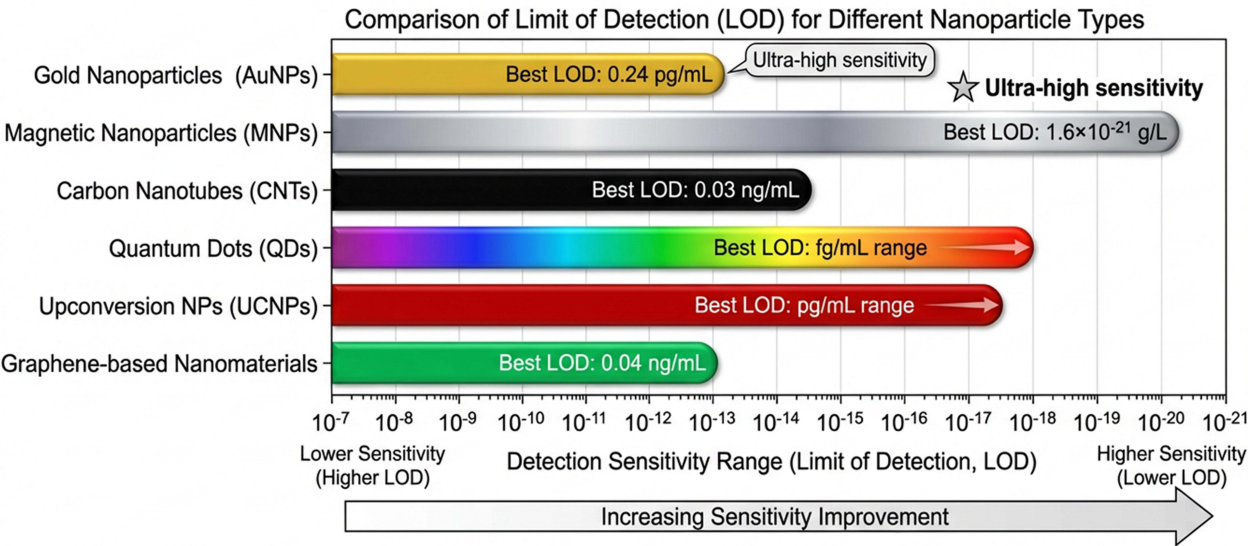


Figure 5 Comparative detection sensitivity of nanoparticle-based analytical methods expressed as the limit of detection (LOD). The best reported LOD ranges for commonly used nanomaterials, including gold nanoparticles (AuNPs), magnetic nanoparticles (MNPs), carbon nanotubes (CNTs), quantum dots (QDs), upconversion nanoparticles (UCNPs), and graphene-based nanomaterials. Sensitivity increases from left to right on a logarithmic scale, with lower LOD values indicating higher analytical sensitivity. AuNPs and MNPs demonstrate ultra-high sensitivity, reaching pg/mL to sub-pg/mL (and lower) detection limits, while QDs and UCNPs achieve fg/mL to pg/mL ranges. CNTs and graphene-based systems show moderate sensitivity in the ng/mL range. Overall, the figure highlights the superior sensitivity achievable with metallic and luminescent nanoparticle platforms compared with carbon-based nanomaterials.

safeguarding food safety, especially in food like peanuts, grains, and dairy products that are particularly vulnerable to AF contamination.

Sample Preparation Techniques

Sample preparation is a pivotal step in the detection of AFs, as it can significantly influence the accuracy and reliability of results. Various methods have been employed across different studies. For instance, Wang et al⁶⁹ crushed peanut samples and extracted AF from them using a methanol/water solution, a straightforward yet effective technique. In contrast, Wu et al⁴⁰ opted for a 50% methanol solution, illustrating the diversity of approaches used to isolate AFs from food matrices. Other studies adopted more complex and rigorous procedures and these meticulous preparation methods underscore the necessity for thorough protocols to ensure reliable extraction of AFs from food products.

Types of Food Samples Tested

Table 1 demonstrates the extensive variety of food matrices assessed for AF contamination, encompassing cereal grains such as maize, rice, and wheat; oilseed crops including peanuts and soybeans; as well as dairy-derived products like milk. The prevalence of AFs in these foods highlights the critical need for ongoing monitoring and assessment. Studies conducted by Feng et al⁴¹ focused on grains which form a major component for many staple diets and can significantly impact public health when contaminated with AFs. The diversity of food matrices included in these studies ensures a comprehensive understanding of AF distribution and the associated contamination risks. The findings from such research play a vital role in informing regulatory standards and food safety practices, guiding policymakers, and helping to protect public health.

Detection Methods

The research employs a variety of techniques for identifying AFs, liquid chromatography (LC), immunoassays, and nanoparticles. Each method has its own strengths and weaknesses in terms of sensitivity and specificity. Notably, many of these methods showed strong agreement with established techniques like LC.

Concentration Levels

Levels of AFs recovered from food samples like rice, maize, wheat, and wine varied significantly. While some studies provided specific measurements, others offered broader ranges. For instance, Es'haghi and colleagues³¹ reported specific AFB₁ concentrations in rice and wheat, while Shao et al³⁵ noted varying levels of the same toxin.

Accuracy of Detection

Most studies demonstrated high accuracy in their findings, often aligning closely with LC results. For example, research by Masinde et al³² demonstrated a strong correlation with HPLC, and recovery rates were reported between 79 and above 100%. The accuracy of detection often relied on specific methods and conditions used.

Time Requirements

The time needed for detection varied widely among studies. Some methods could yield results in as little as 5 min,³² while others required up to 2 hrs.⁴⁹ This variation is important for real-world applications where expeditious results can be obtained.

Stability of Nanoparticles

The durability of nanoparticles used in these detection methods was a significant focus. Many studies emphasized how well these nanoparticles performed under different conditions. For instance, UCNPs as highlighted by Wang et al⁶⁹ showed excellent photostability, suggesting their potential for long-term application. Several studies investigated how well these detection methods and nanoparticles maintained their effectiveness over time. For example, Feng et al⁴¹ demonstrated that some methods remained reliable for up to 12 months.

Statistics of Selected Studies

A total of 38 studies were included in this systematic review, covering a 13-year publication period from 2011 to 2023 as shown in Section 3.0, reflecting accelerating research interest in nanoparticle-based AF detection technologies (Figure 6). The included studies represent diverse analytical bases, incorporating experimental and analytical methods that utilize AuNPs, CNTs, MNPs, QDs, UCNPs, polymeric nanoparticles, and nanozyme-based systems to enhance detection performance across various food matrices. Collectively, these studies provide a comprehensive evidence base that reflects the evolution of nanotechnology-enhanced detection platforms and their application in food safety monitoring.

Estimated Frequency of Nanoparticles Use in Included Articles

The distribution of nanoparticle platforms used in AF detection as shown in Figure 7 reveals a clear preference for well-established nanomaterials with proven analytical performance. Gold nanoparticles (AuNPs) are the most frequently employed system (n=15), reflecting their strong optical and electrochemical signal amplification capabilities and broad applicability in colorimetric and electrochemical sensing assays. Magnetic nanoparticles (MNPs) follow closely (n=10), owing to their ability to facilitate efficient target separation, enrichment, and assay simplification. Carbon nanotubes (CNTs) (n=8) and graphene-based nanoparticles (n=6) show moderate utilization, largely driven by their high electrical conductivity and large surface area, which are advantageous for electrochemical biosensing. In contrast, QDs (n=5) and polymeric nanoparticles (n=3) are less frequently reported, underscoring their emerging status and the ongoing challenges related to stability, cost, and large-scale application. Overall, the observed distribution highlights a strong reliance on nanoparticle systems with established reliability and translational potential, while newer nanomaterials continue to gain incremental adoption as detection technologies advance.

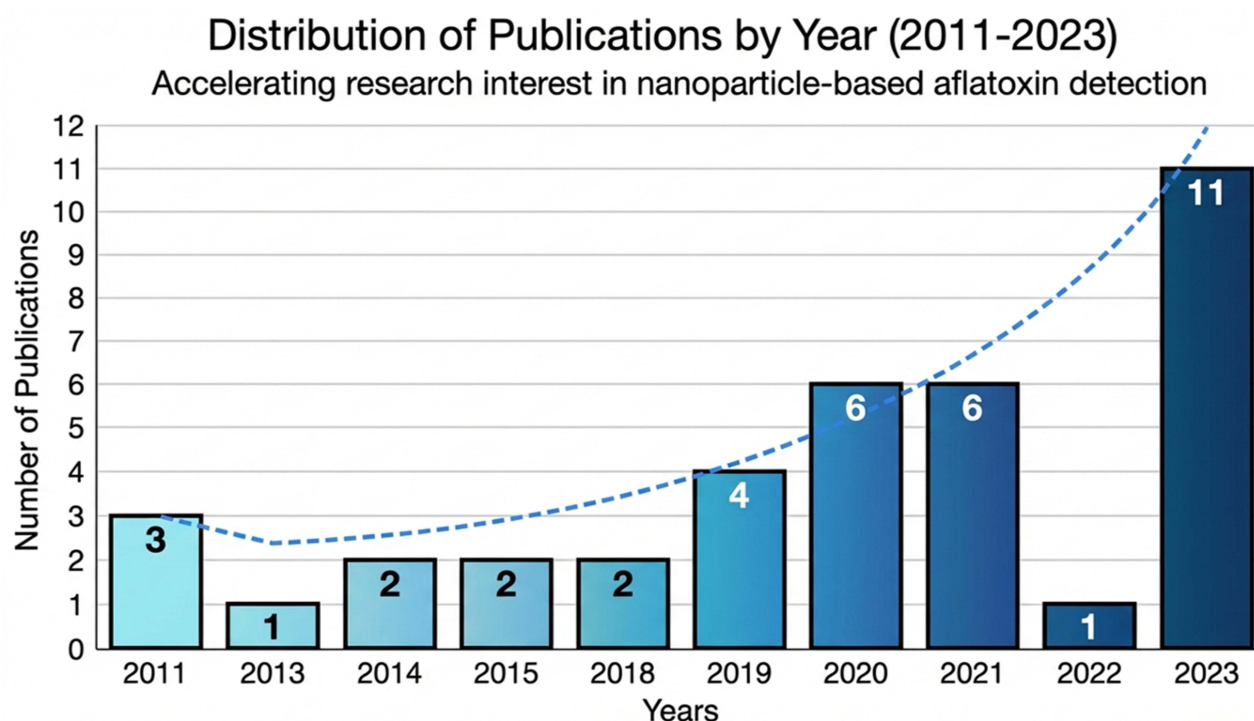


Figure 6 Temporal distribution of articles included in the systematic review on nanoparticle-based aflatoxin detection were published between 2011 and 2023. The number of eligible studies identified per year; while the dashed trend line highlights the overall growth in publications, indicating increasing research interest and activity in this field over time, with a marked rise in recent years.

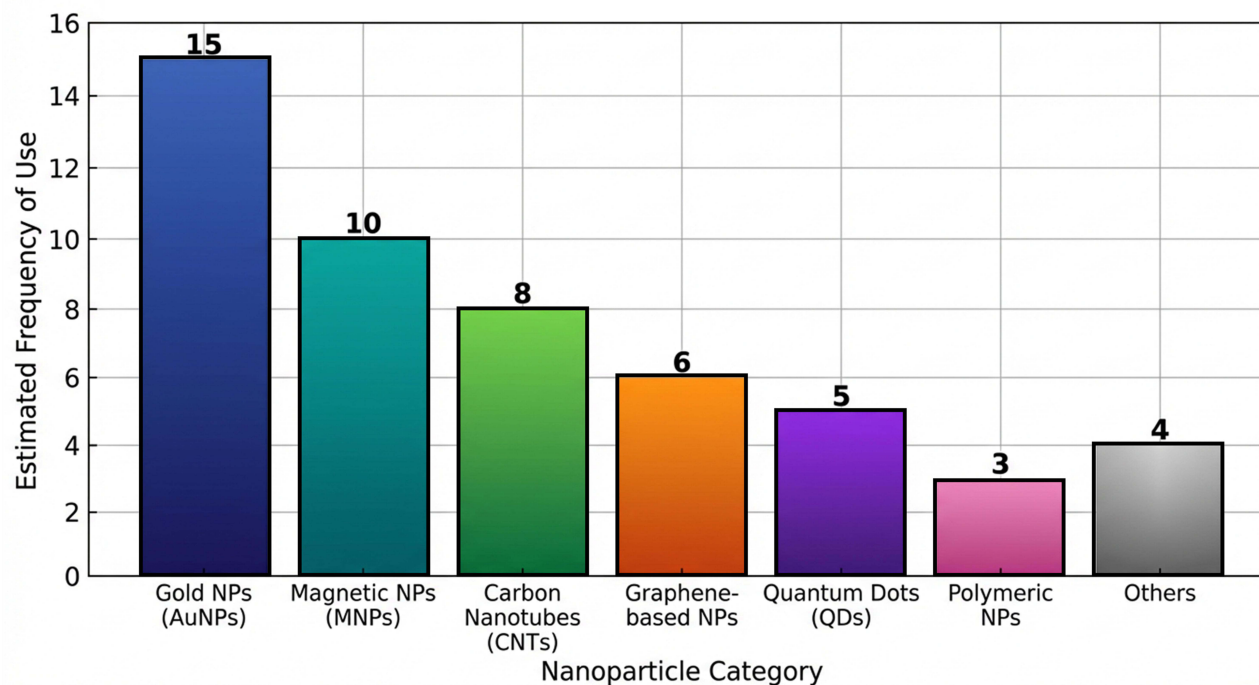


Figure 7 Estimated frequency of nanoparticle uses in aflatoxin detection reported in the included studies. Gold nanoparticles (AuNPs) are the most frequently employed nanomaterials, reflecting their strong optical and electrochemical properties that enable highly sensitive detection. Magnetic nanoparticles (MNPs) and carbon nanotubes (CNTs) are also commonly used due to their separation efficiency and excellent electrical conductivity, respectively. Graphene-based nanoparticles, quantum dots, and polymeric nanoparticles appear less frequently, indicating emerging but comparatively limited application, while other nanoparticle systems are reported sporadically.

Discussion

The systematic review summarized in [Tables 1](#) and [2](#) showcases exciting advancements made in employing nanoparticles to detect AFs in different food commodities. Covering studies from 2011 to 2023, it highlights properties of various nanoparticles, analytical methods, and their effectiveness in AF detection.

Types of Nanoparticles and their Applications

The studies reviewed feature an array of nanoparticles, including AuNPs, MNPs, QDs, and CNTs. Gold nanoparticles are particularly prominent because they are biocompatible and easy to modify, making them suitable for use in immunoassays.⁵⁷

Analysis of the publication years of the included studies indicates a noticeable evolution in the types of nanotechnologies employed between 2010 and 2023. Earlier studies (2010–2015) primarily utilized gold nanoparticles, magnetic nanoparticles, and carbon-based nanomaterials,⁷⁰ while more recent investigations (2020–2023) increasingly feature advanced nanotechnology such as UCNPs, perovskite QDs, nanozyme-based systems, and multifunctional nanobeads.⁷¹ These shifts reflect the rapid technological progression in the field and highlight the potential for future systematic reviews to incorporate formal time-trend analyses to quantify how detection strategies and performance characteristics have improved over time.

Analytical Methods Employed

The studies included reveal a variety of methodologies using nanoparticles, such as functionalized MWCNTs, MNPs, and QDs. Es'haghi et al³¹ used MWCNTs to enhance the extraction and detection of AFB₁ in rice and wheat. Additionally, Zhang et al⁵⁷ found that these nanoparticles, the data generated corroborated well with those generated using LC, underscoring their reliability in detecting various AF at varying concentrations.

These analytical methods range from traditional immunoassays to advanced methods like SERS and electrochemical detection. Immunochromatographic assays are especially favored for their simplicity and speed.^{36,71} Some methods report impressive LODs and for example, Chen et al⁶⁵ achieved an LOD of 0.24 pg/mL for AFB₁ using gold-silica core-shell nanoparticles.

Sensitivity and Specificity

In food safety, sensitivity is crucial, as even low levels of contaminants can pose significant health risks. Many studies report high sensitivity, with several methods reaching LODs within the pg/mL range.^{67,69} This high sensitivity is vital for detecting mycotoxins, particularly those that can be harmful at very low concentrations. Thus, the specificity of these detection methods is impressive. Techniques like SERS and FRET have shown high specificity, reducing the chances of false positives.⁷² This is particularly important in complex food matrices, where other interfering compounds during detection of analytes of interest. This highlighted how versatile nanoparticles can be when detecting AFs across different food matrices.

Detection limits for AFB₁ vary widely among studies, ranging from an astonishing 9 to 20 pg/mL. For example, Zhou et al⁷¹ reported an LOD of 9 pg/mL, indicating a robust method for identifying AFB₁ in challenging matrices like peanut and soy milk. In contrast, Urusov et al³⁴ achieved a higher LOD (20 pg/mL) in barley and maize, highlighting the significance of tailoring methods to specific food types. High specificity is essential to avoid cross-reactivity with other mycotoxins. Studies by Zhang et al⁵⁷ used monoclonal antibodies and targeted extraction techniques to ensure high specificity for AFB₁, minimizing interference from related mycotoxins, crucial for regulatory compliance and consumer safety.

Sample Preparation Techniques

The review also discusses various sample preparation methods, including methanol-water extraction, immunoaffinity cleanup, and ultrasonication. Shao et al³⁵ effectively prepared maize samples spiked with AFB₁ using a methanol-water extraction method. The use of immunoaffinity columns, as seen in studies by Li et al⁶⁷ and Wang et al⁶⁴ further enhances sample purity and specificity before analysis.

Cross Reactivity, Sensitivity and Recovery Rates

Recovery rates are crucial for assessing detection methods. Several studies reported recovery rates exceeding 90%, indicating high sensitivity.⁴¹ For example, Shao et al³⁵ achieved recovery rates between 81.77 and 119.70% for AFB₁, demonstrating the robustness of nanoparticle-based assays. Several studies noted issues with cross-reactivity involving other mycotoxins, complicating the detection of AFB₁. As reported by Gang et al³⁶ significant cross-reactivity with other AFs, stressing the need for methods capable of differentiating AFB₁ in the presence of other toxins. Conversely, research by Wang et al⁴⁴ highlighted negligible cross-reactivity, showcasing improvements in method specificity. The sensitivity of these detection methods is noteworthy, with several studies reporting IC₅₀ values for AFB₁ detection. Shao et al³⁵ noted an IC₅₀ of 38.98 pg/mL, indicating a highly sensitive method capable of detecting low AFB₁ levels in food matrices.

Time Efficiency and Stability

Detection times can vary significantly, with some methods allowing for results to be obtained within minutes.^{32,36} For instance, Urusov et al³⁴ noted that immunoassays could be completed in as little as 5 min, a major advantage in food safety testing. Additionally, nanoparticle stability is critical; many studies, including those by Wu et al⁴⁰ and Chen et al⁶⁵ reported good stability under various conditions such as (Surface Functionalization, pH Stability, ionic Strength, Temperature Control, Reducing Nonspecific Binding, Size and Shape Optimization, Proper Storage Conditions, Choice of Material), making them practical for real-world applications.

Methodological Variability and Impact on Detection Performance

Across the reviewed studies, differences in nanoparticle characteristics, analytical techniques, and sample-preparation procedures were the main sources of variability, leading to inconsistencies in sensitivity, recovery, and limits of detection. Variability in reported LOD and recovery rates across studies can be attributed to differences in nanoparticle design,⁷³ and matrix composition.⁷⁴ Furthermore, sample preparation approaches also contribute to variability.⁷⁵ Differences in food matrices was also responsible for the variability in the in the detection efficacy. For instance, grain matrices contain pigments and polysaccharides that may suppress optical signals;⁷⁶ dairy products introduce lipids and proteins that impede nanoparticle analyte interactions;⁷⁷ and oils present hydrophobic environments that complicate extraction, often leading to elevated LODs and reduced recoveries.⁷⁸ More importantly, nanoparticle properties including size, morphology, surface chemistry, and signal-amplification efficiency directly influence analytical sensitivity, resulting in notable differences in performance with regard to LOD obtained in various studies.⁷⁹

Further variability arises from the use of diverse detection platforms (eg, fluorescence, electrochemical, colorimetric and SERS, each with distinct sensitivity profiles and calibration requirements. Inconsistencies in validation procedures such as spiking levels, recovery studies, and the choice of reference methods (HPLC, ELISA and LC–MS/MS) also hinder direct comparison of results across studies. Fluorescence- and electrochemical-based assays generally achieve lower LODs due to their higher sensitivity compared with colorimetric methods.⁸⁰ As an example, the higher LOD reported by Urusov et al³⁴ relative to Zhou et al⁷¹ can be attributed to differences in nanoparticle properties, matrix-cleanup efficiency, and the sensitivity of the detection system employed. Urusov et al³⁴ used a nanoparticle configuration and detection platform with lower signal responsiveness, coupled with a more complex matrix and less rigorous cleanup strategy, whereas Zhou et al⁷¹ employed highly responsive fluorescent nanomaterials and more sensitive instrumentation, enabling superior detection limits. These observations underscore the need for standardized protocols in nanoparticle synthesis, sample preparation, and method validation. Adoption of harmonized reporting guidelines would enhance comparability, improve reproducibility, and support more consistent evaluation of nanoparticle-based AF detection methods.

Across the included studies, evidence regarding nanoparticle stability varied substantially, as most investigations did not perform formal long-term stability assessments. Nonetheless, a general pattern was apparent. Gold nanoparticles (AuNPs), MNPs, and carbon-based nanomaterials consistently exhibited strong chemical and colloidal stability, maintaining functional integrity over extended periods.^{32,57,81} In contrast, quantum dots, enzyme-linked nanostructures, and certain hybrid organic–inorganic platforms demonstrated greater susceptibility to degradation, photobleaching, or loss of activity under prolonged storage, exposure to light, or fluctuations in pH.⁸² These observations underscore the need for

more rigorous and standardized evaluation of nanoparticle stability, including systematic assessment of storage conditions, functional lifespan, and resilience to environmental stressors. The development of stability reporting guidelines would enhance cross-study comparability and support the advancement of more robust and reliable nanoparticle-based AF detection systems.

Implications of Improved Aflatoxin Detection Techniques for Public Health, Regulatory Authorities, and Industry

Improvements in the sensitivity, specificity, and overall reliability of AF detection technologies have far-reaching implications for public health systems. Early and accurate identification of contaminated food products enables timely interventions, thereby reducing chronic dietary exposure and lowering the burden of AF-associated health outcomes such as hepatocellular carcinoma, immunosuppression, childhood stunting, and compromised immune function.⁸³ In regions where climatic and environmental conditions favour fungal proliferation particularly sub-Saharan Africa and parts of Asia, enhanced detection capacity strengthens national and regional food-safety surveillance systems.⁸⁴ As confirmed by Assoua et al.⁶⁶ Nirmala and Kaundal,⁸⁵ Adeyeye, Ashaolu and Idowu-Adebayo,⁸⁶ more robust and reliable data allow public health authorities to better understand exposure patterns, identify high-risk populations, and implement targeted prevention and education campaigns.

For regulatory authorities, highly sensitive and standardized analytical methods significantly improve the enforcement of maximum residue limits (MRLs) and facilitate harmonization of food-safety regulations across countries and economic blocs. Advanced detection platforms, including nanoparticle-based assays, immunosensors, and LC-MS/MS techniques, support rapid and accurate border-control screening, reducing the likelihood of contaminated consignments entering the market.⁸⁷ These technologies also generate high-quality evidence for risk assessment, enabling science-based policy decisions, updating of regulatory thresholds, and strengthening compliance monitoring along the food and feed chain.⁸⁸

From an industry perspective, improved AF detection methods enhance routine quality-control processes and reduce financial losses associated with rejected shipments, reduced shelf life, and costly product recalls.⁸⁹ The integration of rapid, field-deployable nanoparticle-based assays enables producers, processors, and exporters to monitor contamination at multiple critical control points from pre-harvest through storage, processing, and distribution, supporting proactive rather than reactive mycotoxin-management strategies. For example, modern magnetic relaxation-switching sensors combine gadolinium-based metal-organic frameworks with ultra-small superparamagnetic iron oxide nanoparticles to enhance magnetic relaxation signals, yielding a detection limit of ~0.54 pg/mL for AFB₁.⁹⁰ Newer artificial intelligence-enabled microsphere imaging immunosensors enrich AFs on Fe₃O₄@MIL-101(Fe) nanoparticles and count magnetic microspheres via computer vision, achieving ~4.9 pg/mL and LOD of 0.01–500 ng/mL for AFB₁ in peanuts.⁹¹

These innovations also improve traceability, strengthen supplier accountability, and build consumer trust in the safety and integrity of food product. Collectively, these advancements underscore the transformative potential of emerging detection platforms in supporting safer food systems, more effective regulatory oversight, and a more resilient agricultural and food-processing industry. As climate change continues to influence the ecology of AF-producing fungi, the availability of sensitive, rapid, and scalable detection technologies will be essential for protecting public health, promoting fair trade, and safeguarding food security globally.

Limitations and Recommendation

While the findings of this review are encouraging, several important limitations should be highlighted. The effectiveness of nanoparticle-based detection methods can be influenced by interfering analytes very often present in complex food matrices, which may compromise accuracy in detecting the analytes of interest. Although many studies reported high recovery rates, variability in recovery at different concentrations limits the generalizability of these results. Future research should therefore prioritize standardized protocols and improved specificity in nanoparticle assays for AF detection.

Beyond these analytical challenges, several methodological limitations warrant consideration. Firstly, substantial heterogeneity in nanoparticle types, analytical platforms, food matrices, and reporting formats across the included studies precluded the use of a formal statistical meta-analysis, necessitating reliance on descriptive and thematic synthesis.

Secondly, inconsistencies in reporting of key analytical parameters such as LODs, recovery rates, and calibration procedures restricted the degree to which direct comparisons could be made among studies. Thirdly, despite the use of a comprehensive, multi-database search strategy, the potential for publication bias cannot be ruled out, as studies with negative or non-significant findings may be underrepresented in the published literature. To strengthen future work in this field, standardized reporting of nanoparticle characterization, analytical performance metrics, and validation methods is recommended. Enhancing methodological transparency, adopting harmonized detection protocols, and promoting inter-laboratory validation studies will improve comparability, reproducibility, and the overall robustness of evidence in nanotechnology-based AF detection.

A key priority for advancing nanoparticle-based AF detection is the establishment of international collaboration and multi-laboratory validation efforts. Most methods reported in the literature have been tested within single laboratories or limited regional contexts, which restricts the generalizability of their performance. Coordinated inter-laboratory studies conducted across different countries, food systems, and analytical environments would enable more rigorous assessment of method reproducibility, robustness, and cross-matrix reliability. Such collaborative initiatives are essential for developing globally harmonized protocols, facilitating regulatory acceptance, and ensuring that detection methods perform consistently under diverse real-world conditions. International standard-setting bodies and research networks could play a pivotal role in promoting these validation frameworks, ultimately strengthening global food-safety monitoring systems.

Conclusion

This review demonstrates that AuNPs, MNPs, and carbon-based nanomaterials (particularly graphene and CNTs) are among the best-performing nanotechnologies for AF detection due to their high sensitivity, selectivity, rapid signal response, and consistently low LODs across multiple food matrices. Across the included studies, the LODs ranged from 0.03 ng/mL to 20 pg/mL, representing a span from low nanogram to picogram sensitivity in detecting AFs. Repeatability, as inferred from reported recovery experiments, was generally robust (approximately 81.77 to 119.70% recovery), although few studies reported %RSD values for precision. In contrast, other nanomaterials such as polymeric nanoparticles, QDs, and hybrid nano-bioconjugates remain relatively underexplored and unoptimized. These underutilized approaches often face unresolved challenges in stability and reproducibility, and they lack extensive validation in real-world food systems; for instance, no aptamer-based or molecularly imprinted polymer (MIP)-based mycotoxin test kits have yet reached the market. This gap underscores the need for further research into these promising but less-studied nanotechnologies.

Despite the significant technical progress demonstrated by nano-sensors, commercialization of mycotoxin nanosensors remains very limited. To move from laboratory success to practical use, future work must prioritize rigorous validation of nanoparticle-based methods under standardized protocols (eg Association of Official Analytical Collaboration (AOAC) or International Organization for Standardization (ISO) guidelines), including inter-laboratory comparisons and large-scale field trials. Engagement with food safety regulators early in the development process will be critical to harmonize testing requirements and integrate nanotechnology-enabled assays into existing surveillance frameworks. Clear guidelines and collaborative studies with regulatory agencies can streamline approval pathways, facilitating industry uptake of these novel sensors. Additionally, the emergence of artificial intelligence (AI)-enabled sensors is opening new avenues for mycotoxin detection. Integrating machine learning algorithms and IoT-based smart sensors with nanoparticle assays can enable automated, real-time analysis and early warning of contamination. Such AI-enhanced platforms, coupled with the proven sensitivity of nanoparticle systems, could greatly improve detection accuracy and efficiency, allowing proactive food safety interventions. Overall, the continued innovation and regulatory integration of the most promising nanoparticle sensors, now potentially augmented by AI analytics are poised to transform AF monitoring. These advances will not only ensure more reliable and ultra-sensitive detection of AFs but also bolster food safety management and public health protection on a global scale.

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1. Gbashi S, Adebo O, Adebisi JA, et al. Food safety, food security and genetically modified organisms in Africa: a current perspective. *Biotechnol Genet Eng Rev.* **2021**;37(1):30–63. doi:10.1080/02648725.2021.1940735
2. Njobeh PB, Dutton F, Michael DHM. *Mycotoxins and Human Health: Significance, Prevention and Control*. 1st edn. **2010**.
3. Njobeh PB, Dutton MF, Koch SH, Chuturgoon A, Stoev S, Seifert K. Contamination with storage fungi of human food from Cameroon. *Int J Food Microbiol.* **2009**;135(3):193–198. doi:10.1016/j.ijfoodmicro.2009.08.001
4. Penagos-Tabares F, Khiaosa-Ard R, Nagl V, et al. Mycotoxins, phytoestrogens and other secondary metabolites in Austrian pastures: occurrences, contamination levels and implications of geo-climatic factors. *Toxins.* **2021**;13(7):460. doi:10.3390/toxins13070460
5. Makun HA, Dutton MF, Njobeh PB, Gbodi TA. Aflatoxin contamination in foods and feeds: focus on Africa. In: Hafi A, editor. *Trends in Vital Food and Control Engineering*. InTech; **2012**.
6. Ramadan NA, Al-Ameri HA. *Aflatoxins-Occurrence, Detoxification, Determination and Health Risks*. IntechOpen; **2022**.
7. Dabuo B, Avogo EW, Koomson GO, Akantibila M, Gbati DA. Aflatoxins: toxicity, occurrences and chronic exposure. In: Abdulla'uf LB, editor. *Aflatoxins-Occurrence, Detection and Novel Detoxification Strategies*. 1st edn. IntechOpen; **2022**. doi:10.5772/intechopen.105723
8. Benkerroum N. Chronic and acute toxicities of aflatoxins: mechanisms of action. *Int J Environ Res Public Health.* **2020**;17(2):423. doi:10.3390/ijerph17020423
9. Kumar P, Mahato DK, Kamle M, Mohanta TK, Kang SG. Aflatoxins: a global concern for food safety, human health and their management. *Front Microbiol.* **2017**;7:1–10. doi:10.3389/fmicb.2016.02170
10. Grace D. Food safety in low and middle income countries. *Int J Environ Res Public Health.* **2015**;12(9):10490–10507. doi:10.3390/ijerph120910490
11. Thompson WJ, Varma V, Joerin J, et al. Smallholder farmer resilience to extreme weather events in a global food value chain. *Clim Change.* **2023**;176(11):152. doi:10.1007/s10584-023-03586-1
12. Dong L. Toward resilient agriculture value chains: challenges and opportunities. *Prod Oper Manag.* **2021**;30(3):666–675. doi:10.1111/poms.13308
13. Kizis D, Vichou AE, Natskoulis PI. Recent advances in mycotoxin analysis and detection of mycotoxigenic fungi in grapes and derived products. *Sustainability.* **2021**;13(5):1–26. doi:10.3390/su13052537
14. Bezuneh TT, Fereja TH, Kitte SA, Li H, Jin Y. Gold nanoparticle-based signal amplified electrochemiluminescence for biosensing applications. *Talanta.* **2022**;248:5625):123611. doi:10.1016/j.talanta.2022.123611
15. Oon YL, Oon YS, Ayaz M, Deng M, Li L, Song K. Waterborne pathogens detection technologies: advances, challenges, and future perspectives. *Front Microbiol.* **2023**;14:1286923. doi:10.3389/fmicb.2023.1286923
16. Mamalis AG. Recent advances in nanotechnology. *J Mater Process Technol.* **2007**;181(1–3):52–58. doi:10.1016/j.jmatprotec.2006.03.052
17. Chen BH, Inbaraj BS. Recent trends in analysis of mycotoxins in food using carbon-based nanomaterials. *J Food Drug Anal.* **2022**;30(4):562–589. doi:10.38212/2224-6614.3437
18. Perfézou M, Turner A, Merkoçi A. Cancer detection using nanoparticle-based sensors. *Chem Soc Rev.* **2012**;41(7):2606–2622. doi:10.1039/C1CS15134G
19. Nguyen KT, Zhao Y. Engineered hybrid nanoparticles for on-demand diagnostics and therapeutics. *Acc Chem Res.* **2015**;48(12):3016–3025. doi:10.1021/acs.accounts.5b00316

20. Bigdeli A, Ghasemi F, Golmohammadi H, et al. Nanoparticle-based optical sensor arrays. *Nanoscale*. 2017;9(43):16546–16563. doi:10.1039/c7nr03311g
21. Tagit O, Hildebrandt N. Fluorescence sensing of circulating diagnostic biomarkers using molecular probes and nanoparticles. *ACS Sens*. 2017;2(1):31–45. doi:10.1021/acssensors.6b00625
22. Ebrahimi F, Kumari A, Dellinger K. Integration of nanoengineering with artificial intelligence and machine learning in surface-enhanced Raman spectroscopy (SERS) for the development of advanced biosensing platforms. *Adv Sensor Res*. 2025;4(2):1–17. doi:10.1002/adsr.202400155
23. Gopal AR, Joy F, Dutta V, et al. Carbon dot-based fluorescence resonance energy transfer (FRET) systems for biomedical, sensing, and imaging applications. *Part Part Syst Charact*. 2024;41(1):1–24. doi:10.1002/ppsc.202300072
24. Yao F, Zhu P, Chen J, et al. Synthesis of nanoparticles via microfluidic devices and integrated applications. *Mikrochim Acta*. 2023;190(7):256. doi:10.1007/s00604-023-05838-4
25. Page MJ, Shamseer L, Tricco AC. Registration of systematic reviews in PROSPERO: 30,000 records and counting. *Syst Rev*. 2018;7(1). doi:10.1186/s13643-018-0699-4
26. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*. 2021;372:n71. doi:10.1136/bmj.n71
27. Aromataris E, Lockwood C, Porritt K, Pilla B, Jordan Z. JBI Manual for Evidence Synthesis. *JBI*. 2024;2024:1.
28. Haddaway NR, Kohl C, Rebelo Da Silva N, et al. A framework for stakeholder engagement during systematic reviews and maps in environmental management. *Environ Evid*. 2017;6(1). doi:10.1186/s13750-017-0089-8
29. Covidence. *A Practical Guide: Data Extraction for Intervention Systematic Reviews*; 2024.
30. Barker TJ, Hasanoff S, Aromataris E, et al. The revised JBI critical appraisal tool for the assessment of risk of bias for analytical cross-sectional studies. *JBI Evid Synth*. 2025. doi:10.11124/JBIES-24-00523
31. Es'haghi Z, Sorayaei H, Samadi F, Masrounia M, Bakherad Z. Fabrication of a novel nanocomposite based on sol-gel process for hollow fiber-solid phase microextraction of aflatoxins: B1 and B2, in cereals combined with high performance liquid chromatography-diode array detection. *J Chromatogr B*. 2011;879(28):3034–3040. doi:10.1016/j.jchromb.2011.08.042
32. Masinde LA, Sheng W, Xu X, et al. Colloidal gold based immunochromatographic strip for the simple and sensitive determination of aflatoxin B1 and B2 in corn and rice. *Mikrochim Acta*. 2013;180(9–10):921–928. doi:10.1007/s00604-013-1008-5
33. Hashemi M, Taherimaslak Z. Determination of aflatoxin M1 in liquid milk using high performance liquid chromatography with fluorescence detection after magnetic solid phase extraction. *RSC Adv*. 2014;4(63):33497–33506. doi:10.1039/C4RA04254A
34. Urusov AE, Petrakova AV, Vozniak MV, Zherdev AV, Dzantiev BB. Rapid immunoassay of aflatoxin B1 using magnetic nanoparticles. *Sensors*. 2014;14(11):21843–21857. doi:10.3390/s141121843
35. Shao Y, Duan H, Guo L, Leng Y, Lai W. Quantum dot nanobead-based multiplexed immunochromatographic assay for simultaneous detection of aflatoxin B1 and zearalenone. *Anal Chim Acta*. 2018;1025:163–171. doi:10.1016/j.aca.2018.03.041
36. Xiao G, Zhao Y, Li L, Pratt JO, Su H, Tan T. Facile synthesis of dispersed Ag nanoparticles on chitosan-TiO2 composites as recyclable nanocatalysts for 4-nitrophenol reduction. *Nanotechnology*. 2018;29(15):155601. doi:10.1088/1361-6528/aaac74
37. Wang F, Han Y, Wang S, Ye Z, Wei L, Xiao L. Single-particle LRET aptasensor for the sensitive detection of aflatoxin B1 with upconversion nanoparticles. *Anal Chem*. 2019;91(18):11856–11863. doi:10.1021/acs.analchem.9b02599
38. Khan IM, Niazi S, Yu Y, et al. Aptamer induced multicolored AuNCs-WS2 “turn on” FRET nano platform for dual-color simultaneous detection of aflatoxin B1 and zearalenone. *Anal Chem*. 2019;91(21):14085–14092.
39. Ren W, Li Z, Xu Y, et al. One-step ultrasensitive bioluminescent enzyme immunoassay based on nanobody/nanoluciferase fusion for detection of aflatoxin B1 in cereal. *J Agric Food Chem*. 2019;67(18):5221–5229. doi:10.1021/acs.jafc.9b00688
40. Wu L, Zhou M, Wang Y, Liu J. Nanozyme and aptamer-based immunosorbent assay for aflatoxin B1. *J Hazard Mater*. 2020;399:123154. doi:10.1016/j.jhazmat.2020.123154
41. Feng Y, He L, Wang L, et al. Detection of aflatoxin B1 based on a porous anodized aluminum membrane combined with surface-enhanced Raman scattering spectroscopy. *Nanomaterials*. 2020;10(5):1000. doi:10.3390/nano10051000
42. Akgözüllü S, Yavuz H, Denizli A. SPR nanosensor based on molecularly imprinted polymer film with gold nanoparticles for sensitive detection of aflatoxin B1. *Talanta*. 2020;219:121219. doi:10.1016/j.talanta.2020.121219
43. Lin B, Kannan P, Qiu B, Lin Z, Guo L. On-spot surface enhanced Raman scattering detection of aflatoxin B1 in peanut extracts using gold nanobipyramids evenly trapped into the AAO nanoholes. *Food Chem*. 2020;307:125528. doi:10.1016/j.foodchem.2019.125528
44. Wang X, Wu X, Lu Z, Tao X. Comparative study of time-resolved fluorescent nanobeads, quantum dot nanobeads and quantum dots as labels in fluorescence immunochromatography for detection of aflatoxin B1 in grains. *Biomolecules*. 2020;10(4):575. doi:10.3390/biom10040575
45. Xu Z, Long L, Chen Y, Chen ML, Cheng YH. Corrigendum to “a nanozyme-linked immunosorbent assay based on metal-organic frameworks (MOFs) for sensitive detection of aflatoxin B1”. *Food Chem*. 2021;346:128931. doi:10.1016/j.foodchem.2020.128931
46. Wu J, Ali S, Ouyang Q, Wang L, Rong Y, Chen Q. Highly specific and sensitive detection of aflatoxin B1 in food based on upconversion nanoparticles-black phosphorus nanosheets aptasensor. *Microchem J*. 2021;171:106847. doi:10.1016/j.microc.2021.106847
47. Jia B, Liao X, Sun C, Fang L, Zhou L, Kong W. Development of a quantum dot nanobead-based fluorescent strip immunosensor for on-site detection of aflatoxin B1 in lotus seeds. *Food Chem*. 2021;356:129614. doi:10.1016/j.foodchem.2021.129614
48. Zhao S, Bu T, He K, et al. A novel α -Fe2O3 nanocubes-based multiplex immunochromatographic assay for simultaneous detection of deoxynivalenol and aflatoxin B1 in food samples. *Food Control*. 2021;123:107811. doi:10.1016/j.foodcont.2020.107811
49. Li R, Wen Y, Wang F, He P. Recent advances in immunoassays and biosensors for mycotoxins detection in feedstuffs and foods. *J Anim Sci Biotechnol*. 2021;12(1):1–19. doi:10.1186/s40104-021-00629-4
50. Qian J, Liu Y, Cui H, et al. Fabrication of a disposable aptasensing chip for simultaneous label-free detection of four common coexisting mycotoxins. *Anal Chim Acta*. 2023;1282:341921. doi:10.1016/j.aca.2023.341921
51. Zhao D, Xu X, Wang X, Xu B, Zhang F, Wu W. Synthesis of a core-shell magnetic covalent organic framework for the enrichment and detection of aflatoxin in food using HPLC-MS/MS. *Mikrochim Acta*. 2023;190(12):1–11. doi:10.1007/s00604-023-06051-z
52. Lv X, Tan F, Miao T, et al. In situ generated PtNPs to enhance electrochemiluminescence of multifunctional nanoreactor COP T4VTP6 for AFB1 detection. *Food Chem*. 2023;399:134002. doi:10.1016/j.foodchem.2022.134002

53. He P, Mehedi Hassan M, Yang W, et al. Rapid and stable detection of three main mycotoxins in rice using SERS optimized AgNPs@K30 coupled multivariate calibration. *Food Chem.* **2023**;398:133883. doi:10.1016/j.foodchem.2022.133883
54. Chen Y, Shen Y, Wang H, Zhang J, Zhu J. A novel dual-channel immunochromatographic strip using up-conversion nanoparticles for simultaneous detection of AFB1 and ZEN in maize. *Anal Bioanal Chem.* **2023**;415(20):4935–4947. doi:10.1007/s00216-023-04799-0
55. Gao J, He S, Nag A, Wong JWC. A review of the use of carbon nanotubes and graphene-based sensors for the detection of aflatoxin m1 compounds in milk. *Sensors.* **2021**;21(11):3602. doi:10.3390/s21113602
56. Lu Y, Chen R, Dong Y, et al. Magnetic relaxation switching immunoassay based on “limited-magnitude” particles for sensitive quantification of aflatoxin B1. *Anal Chim Acta.* **2023**;1266:341329. doi:10.1016/j.aca.2023.341329
57. Zhang D, Li P, Zhang Q, Zhang W. Ultrasensitive nanogold probe-based immunochromatographic assay for simultaneous detection of total aflatoxins in peanuts. *Biosens Bioelectron.* **2011**;26(6):2877–2882. doi:10.1016/j.bios.2010.11.031
58. Ji Y, Ren M, Li Y, et al. Detection of aflatoxin B1 with immunochromatographic test strips: enhanced signal sensitivity using gold nanoflowers. *Talanta.* **2015**;142:206–212. doi:10.1016/j.talanta.2015.04.048
59. Majzik A, Hornok V, Sebok D, et al. Sensitive detection of aflatoxin B1 molecules on gold SPR chip surface using functionalized gold nanoparticles. *Cereal Res Commun.* **2015**;43(3):426–437. doi:10.1556/0806.43.2015.3.8
60. Lu L, Yu R, Zhang L. AFB1 colorimetric aptamer sensor for the detection of AFB1 in ten different kinds of miscellaneous beans based on gold nanoparticles and smartphone imaging. *Food Chem.* **2023**;421:136205. doi:10.1016/j.foodchem.2023.136205
61. Qian J, Ren C, Wang C, et al. Gold nanoparticles mediated designing of versatile aptasensor for colorimetric/electrochemical dual-channel detection of aflatoxin B1. *Biosens Bioelectron.* **2020**;166:112443. doi:10.1016/j.bios.2020.112443
62. Xu Z, Yu S, Xie X, et al. Target-triggered Fe3O4@NPC-UCNPs assembly for photoactivatable biosensing of aflatoxin B1. *Chem Eng J.* **2023**;470:144028. doi:10.1016/j.cej.2023.144028
63. Hua Z, Yu T, Liu D, Xianyu Y. Recent advances in gold nanoparticles-based biosensors for food safety detection. *Biosens Bioelectron.* **2021**;179:113076. doi:10.1016/j.bios.2021.113076
64. Wang G, He X, Wang L, et al. Non-enzymatic electrochemical sensing of glucose. *Mikrochim Acta.* **2013**;180(3–4):161–186. doi:10.1007/s00604-012-0923-1
65. Chen R, Wang H, Sun C, et al. Au@SiO2 SERS nanotags based lateral flow immunoassay for simultaneous detection of aflatoxin B1 and ochratoxin A. *Talanta.* **2023**;258:124401. doi:10.1016/j.talanta.2023.124401
66. Assoua JE, Bomdzele E, Omosehin O, et al. Integrating climate change, food safety, nutrition, and health outcomes in food systems policies and programs in Africa. *World Food Policy.* **2024**;10(1):86–110. doi:10.1002/wfp2.12068
67. Li X, Zhang M, Mo H, Li H, Xu D, Hu L. The ultrasensitive detection of aflatoxin M1 using gold nanoparticles modified electrode with Fe3+ as a probe. *Foods.* **2023**;12(13):2521. doi:10.3390/foods12132521
68. Kim CY, Shaban SM, Cho SY, Kim DH. Detection of periodontal disease marker with geometrical transformation of Ag nanoplates. *Anal Chem.* **2023**;95(4):2356–2365. doi:10.1021/acs.analchem.2c04327
69. Wang Y, Zhu F, Yin L, et al. Ratiometric fluorescent detection of pesticide based on split aptamer and magnetic separation. *Sens Actuators B Chem.* **2022**;367:132045. doi:10.1016/j.snb.2022.132045
70. Fritea L, Banica F, Costea TO, et al. Metal nanoparticles and carbon-based nanomaterials for improved performances of electrochemical (bio) sensors with biomedical applications. *Materials.* **2021**;14(21):6319. doi:10.3390/ma14216319
71. Zhou H, Liu N, Yan Z, et al. Development and validation of the one-step purification method coupled to LC-MS/MS for simultaneous determination of four aflatoxins in fermented tea. *Food Chem.* **2021**;354:129497. doi:10.1016/j.foodchem.2021.129497
72. Tang Y, Yao L, Wang Y, et al. Signal-on lateral flow immunoassays for rapid detection of tetrodotoxin in pufferfish. *J Hazard Mater.* **2025**;486:136973. doi:10.1016/j.jhazmat.2024.136973
73. Laycock A, Clark NJ, Clough R, Smith R, Handy RD. Determination of metallic nanoparticles in biological samples by single particle ICP-MS: a systematic review from sample collection to analysis. *Environ Sci Nano.* **2022**;9(2):420–453. doi:10.1039/D1EN00680K
74. Williams ML, Olomukoro AA, Emmons RV, Godage NH, Gionfriddo E. Matrix effects demystified: strategies for resolving challenges in analytical separations of complex samples. *J Sep Sci.* **2023**;46(23):e2300571. doi:10.1002/jssc.202300571
75. Gegenschatz SA, Chiappini FA, Teglia CM, Muñoz de la Peña A, Goicoechea HC. Binding the gap between experiments, statistics, and method comparison: a tutorial for computing limits of detection and quantification in univariate calibration for complex samples. *Anal Chim Acta.* **2022**;1209:339342. doi:10.1016/j.aca.2021.339342
76. Singh Purewal S, Singh RS. *Colored Cereals*. CRC Press; **2025**; doi:10.1201/9781003454922
77. Girigoswami A, Ghosh MM, Pallavi P, Ramesh S, Girigoswami K. Nanotechnology in detection of food toxins – focus on the dairy products. *Biointerface Res Appl Chem.* **2021**;11(6):14155–14172. doi:10.33263/BRIAC116.1415514172
78. Lavenburg VM, Rosentrater KA, Jung S. Extraction methods of oils and phytochemicals from seeds and their environmental and economic impacts. *Processes.* **2021**;9(10):1839. doi:10.3390/pr9101839
79. Hoang TX, Phan LMT, TAT V, Cho S. Advanced signal-amplification strategies for paper-based analytical devices: a comprehensive review. *Biomedicines.* **2021**;9(5):540. doi:10.3390/biomedicines9050540
80. Hassan MH, Khan R, Andreescu S. Advances in electrochemical detection methods for measuring contaminants of emerging concerns. *Electrochem Sci Adv.* **2022**;2(6):1–27. doi:10.1002/elsa.202100184
81. Li Y, Wang N, Liu J, Hou X. Demystifying neural style transfer. IJCAI International Joint Conference on Artificial Intelligence. **2017**;2017:2230–2236. doi:10.24963/ijcai.2017/310.
82. Cruz-Cruz A, Rivas-Sanchez A, González-González RB, Parra-Saldívar R. Tuning catalytic attributes of enzymes by conjugation with functionalized carbon dots. *Top Catal.* **2025**;68(9–10):916–928. doi:10.1007/s11244-024-01911-1
83. Kibugu J, Munga L, Mburu D, et al. Dietary mycotoxins: an overview on toxicokinetics, toxicodynamics, toxicity, epidemiology, detection, and their mitigation with special emphasis on aflatoxicosis in humans and animals. *Toxins.* **2024**;16(11):483. doi:10.3390/toxins16110483
84. Ajayeoba TA, Jokodola TT, Olaoye CO, et al. Microbial food safety in Africa amid climate change: risks, innovations, and strategies for resilience. *J Innov Sci Technol.* **2025**;4(1):182–192.
85. Nirmala KS, Kaundal M. Global food security and environmental challenges in the face of climate change. *J Sci Res Rep.* **2025**;31(7):1050–1066. doi:10.9734/jsrr/2025/v31i73321

86. Adeyeye SAO, Ashaolu TJ, Idowu-Adebayo F. Mycotoxins: food safety, consumer health and Africa's food security. *Polycycl Aromat Compd.* **2022**;42(8):5779–5795. doi:10.1080/10406638.2021.1957952
87. El-tahlawy AS, Alawam AS, Rudayn HA, et al. Advanced analytical and digital approaches for proactive detection of food fraud as an emerging contaminant threat. *Talanta Open.* **2025**;12:100499. doi:10.1016/j.talo.2025.100499
88. Trubetskaya A, Hennessy A, Ryan I, Stockil K, Gaskin C. Industrial assessment tools of risks associated with wastewater and water technologies. *ACS ES&T Water.* **2025**;5(10):6131–6151. doi:10.1021/acsestwater.5c00839
89. Gelaye Y. Systematic review on aflatoxin contamination in Ethiopia: current status and implications. *Stud Fungi.* **2024**;9(1). doi:10.48130/sif-0024-0013
90. Dai S, Xing K, Jiao Y, et al. A novel magnetic resonance tuning-magnetic relaxation switching sensor based on Gd-MOF/USPIO assembly for sensitive and convenient aflatoxin B1 detection. *Food Chem.* **2024**;443:138537. doi:10.1016/j.foodchem.2024.138537
91. Dong Y, Ren M, Tu J, Chen Y. Artificial intelligence-enabled microsphere imaging immunosensor based on magnetic metal-organic frameworks-assisted sample pretreatment for detecting aflatoxin B1 in peanuts. *J Hazard Mater.* **2025**;493:138410. doi:10.1016/j.jhazmat.2025.138410

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