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Review

Toward sustainable food safety: Natural ligand–gold nanoparticle plasmonic sensors for on-site mycotoxin detection

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ABSTRACT

Mycotoxins remain a critical challenge to food safety, with limitations in conventional methods driving demand for rapid, portable alternatives. Gold nanoparticle (AuNP)-based sensors, exploiting localized surface plasmon resonance (LSPR) and surface-enhanced Raman scattering (SERS), offer rapid and highly sensitive detection, typically achieving detection limits in the low ppb (μg/kg) to ng/mL range, with performance in food matrices further improved through suitable ligand functionalization and optimized assay design. This review highlights recent advances in the use of natural ligands to design sustainable plasmonic nanosensors for on-site mycotoxin detection. Moreover, natural ligands, such as polyphenols, flavonoids, and organic acids, enable green synthesis while enhancing selectivity and biocompatibility. We discuss structure–function relationships at the ligand–AuNP interface, linking functional groups (hydroxyl, carbonyl, and carboxyl) to stability and specificity. Case studies illustrate improvements in detection limits and applicability in food matrices. Recent trends point toward dual-ligand systems, portable paper-based devices, smartphone integration, and IoT/blockchain-enabled monitoring. Challenges such as reproducibility, standardization, and regulatory approval are considered, alongside opportunities for digital integration and global-scale food safety networks. This review positions metabolite-functionalized plasmonic sensors as a sustainable, next-generation trend in food safety surveillance.

1. Introduction

Mycotoxin contamination is a food safety problem worldwide, affecting cereal grains, nuts, fruits, and spices throughout the production chain. Mycotoxins, including aflatoxins, ochratoxin A, fumonisins, trichothecenes, patulin, citrinin, and zearalenone, are produced by filamentous fungi of the genera *Aspergillus, Fusarium, Penicillium, Claviceps,* and *Alternaria*. These compounds are toxic to humans and animals (El-Sayed et al., 2022; Haque et al., 2020). Mycotoxins can remain stable during food storage and processing, making them difficult to eradicate and entailing greater health risks. A widely cited FAO estimate suggests that approximately 25% of the world's food crops are contaminated with mycotoxins each year, resulting in substantial economic losses and reduced food security (FAO (Food and Agriculture Organization of the United Nations), 2004).

Adverse health outcomes associated with mycotoxins include acute toxicity, immunosuppression, teratogenicity, and carcinogenicity. For example, aflatoxin B1 (AFB1) is classified as a Group 1 human carcinogen by the International Agency for Research on Cancer (IARC) and is associated with hepatocellular carcinoma (Hamid et al., 2013). Ochratoxin A (OTA) is nephrotoxic and immunosuppressive, and *Fusarium* toxins can lead to esophageal cancer or liver or kidney toxicity, depending on the route of exposure and host response (Gupta et al., 2022; Wangia-Dixon & Nishimwe, 2021). Adverse health effects may be worsened in tropical and subtropical regions, such as Malaysia, because the hot and humid climate is conducive to fungal growth and mycotoxin accumulation (Afsah-Hejri et al., 2013).

Strict regulatory limits have been established worldwide to control

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mycotoxin contamination in food and agricultural commodities due to the significant health risks they pose. For instance, the European Commission has set maximum levels of 2 μg/kg for AFB1 in cereals and cereal products intended for direct human consumption. In contrast, the maximum level for total aflatoxins is 4 μg/kg in many food products (European Commission, 2006). Similarly, limits for OTA typically range from 3 to 5 μg/kg in cereal-based foods, depending on the specific commodity and processing conditions (Chain et al., 2020; European Commission, 2006). Fumonisin B1 (FB1), which commonly occurs in maize and maize-based products, is also subject to regulatory control due to its toxicological significance and frequent occurrence in staple food commodities. These stringent regulatory thresholds require analytical methods capable of detecting mycotoxins at very low concentrations, often at the parts-per-billion (ppb)(μg/kg) or lower level, highlighting the need for highly sensitive detection technologies for effective food safety monitoring and regulatory compliance (Shephard, 2016; Turner et al., 2009). Recent studies have shown that AuNP-based plasmonic nanosensors can achieve detection limits in the low-ppb or ng/mL range relevant to regulatory monitoring. For example, reported limits of detection include 0.16 ng/mL for AFB1, 1.43 ng/mL for OTA, and 3.27 ng/mL for FB1, highlighting the potential of these platforms as rapid screening tools for mycotoxin contamination in food samples.

Thus, accurate mycotoxin detection is critical to reduce such risks. Traditional tools, such as high-performance liquid chromatography (HPLC) and enzyme-linked immunosorbent assay (ELISA), remain widely used because of their high sensitivity, established quantitative performance, and regulatory acceptance. However, these methods also have important disadvantages, including high operating costs, time-consuming analyses, and the need for sophisticated instrumentation and qualified personnel (J. Singh & Mehta, 2020; K. Singh & Kumari, 2022). These barriers hinder large-scale, real-time monitoring, particularly in resource-limited regions. Plasmonic nanosensors are primarily considered rapid screening tools that complement rather than replace confirmatory laboratory methods, as challenges related to matrix interference, reproducibility, and regulatory validation still limit their use as standalone analytical platforms. In practical terms, plasmonic sensors are advantageous for rapid preliminary screening and field deployment, whereas HPLC and ELISA remain more suitable for standardized quantitative analysis and regulatory confirmation.

Recent advances in nanomaterial-based sensing technologies have significantly improved the rapid detection of mycotoxins in food matrices. For example, graphene-based paper sensors have been developed for label-free detection of aflatoxin B1 in corn, demonstrating the feasibility of portable sensing platforms for on-site monitoring. Furthermore, dual-mode sensing strategies have been explored to improve analytical reliability. A photothermal–electrochemical aptasensor based on AuNP-modified substrates achieved highly sensitive detection of aflatoxin B1, with picogram-level limits of detection (C. Wang et al., 2022). Colorimetric nanobiosensors have also been widely investigated for their visual detection capability; an Fe_3O_4/graphene oxide and AuNP-based platform has been reported that simultaneously detects AFB1 and OTA in agricultural products (Zhu et al., 2020). In addition, portable fluorescence devices integrated with internet of things (IoT) technology have recently been developed to enable rapid, connected monitoring of OTA and AFB1 in food systems (C. Wang et al., 2024).

Therefore, plasmonic nanosensors based on gold nanoparticles (AuNPs) represent a promising approach to enhancing food safety. These nanosensors leverage the localized surface plasmon resonance (LSPR) optical properties of AuNPs to provide rapid, ultra-sensitive, and visual detection of mycotoxins at low concentrations (Sheikh & Shekarchizadeh, 2025). The small size of AuNPs enables surface modification and embedding them in portable devices for on-site screening (Jalalvand & Karami, 2025). In addition, AuNPs can significantly enhance Raman scattering signals via surface-enhanced Raman scattering (SERS), enabling ultra-sensitive detection of analytes at trace concentrations (Huang et al., 2022; Marin et al., 2021). These optical characteristics, combined with the high surface-to-volume ratio of nanoparticles, allow AuNPs to serve as versatile platforms for developing colorimetric, LSPR-based, and SERS-based sensing systems (Baranwal et al., 2016; Marin et al., 2021).

The performance of AuNP-based sensors is strongly influenced by the ligands used for nanoparticle functionalization. Conventional biological receptors, such as antibodies and aptamers, provide high specificity, but their use is often associated with complex preparation, higher costs, and limited stability under variable environmental conditions. Recently, naturally derived ligands, including plant metabolites such as polyphenols, flavonoids, organic acids, amino acids, and fatty acids, have emerged as promising alternatives. These biocompatible ligands contain reactive functional groups (–OH, C═O, –COOH, –NH_2) that enable green synthesis and stabilization of AuNPs, while also facilitating interactions with mycotoxins via hydrogen bonding, electrostatic interactions, and π–π stacking. Consequently, plant-derived ligands can enhance nanoparticle stability and support toxin recognition while reducing reliance on toxic reagents, promoting the development of more sustainable AuNP-based nanosensors. Despite growing interest in plasmonic nanosensors for food safety applications, a clear understanding of how naturally derived ligands can improve AuNP-based mycotoxin sensing remains lacking. In addition, previous reviews have emphasized either broad SERS-based food-hazard detection or substrate engineering. The specific roles of natural ligands in AuNP-based mycotoxin sensing, as well as current limitations related to reproducibility, matrix interference, scalability, and regulatory acceptance, remain insufficiently discussed. This topic is highly relevant to food safety analysis; it links stringent regulatory detection needs with the development of sustainable, sensitive, and field-deployable plasmonic sensing platforms.

Therefore, this review provides a comprehensive overview of natural ligand–functionalized AuNP plasmonic sensors for detecting mycotoxins in food systems. Particular emphasis is placed on the mechanisms of ligand–toxin interactions, the role of natural metabolites in green nanoparticle synthesis, and the analytical performance of LSPR- and SERS-based sensing platforms. The conceptual framework for these sensing strategies is illustrated in Fig. 1. In addition, recent advances in portable sensing technologies and digital integration strategies are discussed, along with current challenges related to reproducibility, scalability, and regulatory acceptance. By highlighting these aspects, this review provides insights into the development of sustainable, field-deployable nanosensor systems for improving food safety monitoring.

Unlike previous reviews that focused primarily on SERS-based food-hazard detection and substrate engineering, this review highlights AuNP-based mycotoxin nanosensors employing natural or hybrid ligands. It compares ligand classes, including natural extracts, biomolecules, and hybrid linkers, in terms of binding mechanisms, antifouling behavior, and signal transduction on LSPR and SERS platforms, while also discussing analytical performance and translational challenges, including green ligand sourcing, scalability, and regulatory considerations. Although natural ligand functionalization has attracted increasing attention for its sustainability and compatibility with green synthesis strategies, studies that apply natural ligands directly to plasmonic mycotoxin sensing remain limited. Therefore, the approach should be regarded as an emerging research direction rather than an established sensing platform.

2. The evolution and fundamental principles of plasmonic detection in food safety

The previous two decades have seen a rise in the use of plasmonic nanomaterials in food safety. Early research in the 2000s focused on the use of AuNPs as colorimetric indicators because of their unique LSPR properties, which cause visible color changes when they interact with analytes. These early sensors were designed primarily for detecting heavy metals and small organic contaminants. Recently, plasmonic

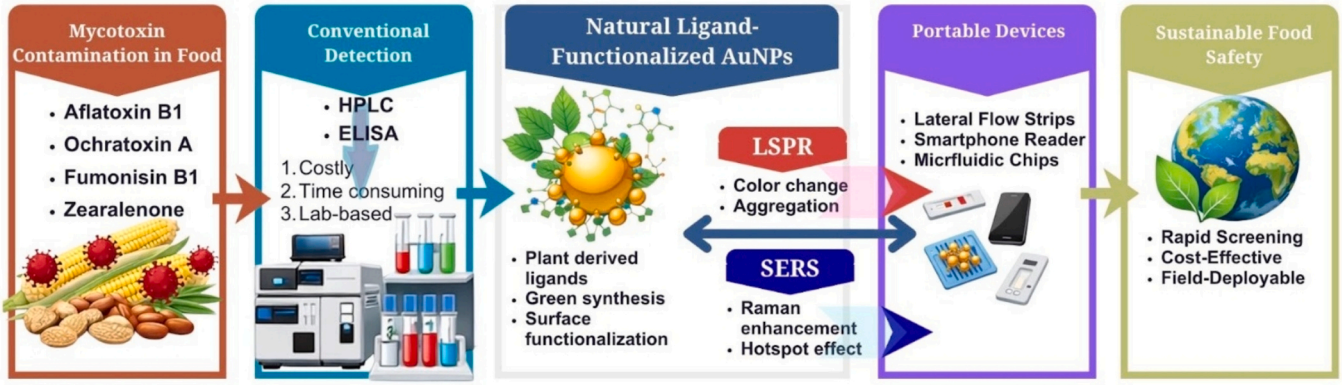

Fig. 1. Conceptual framework of natural ligand-functionalized AuNPs plasmonic sensors for sustainable on-site mycotoxin detection.

nanosensors have moved beyond colorimetric platforms to include SERS-based technologies to enable the detection of mycotoxins, pesticide residues, pathogenic bacteria, and foodborne toxins. Aflatoxin B1, one of the most dangerous mycotoxins, was one of the early analytes detected using colorimetric sensors based on AuNP aggregation, illustrating the potential for nanoplasmonic detection in complex food matrices (Lerdsri et al., 2021).

Nanoplasmonics is concerned with light-modifying metal nanostructures, such as metal nanoparticles that strongly interact with incident light. AuNPs are the most studied nanostructures, as they are a general sensing platform for chemical and biological targets (analytes). The LSPR of AuNPs is due to the collective oscillation of electrons resonating with incident light, which enables strong scattering and absorption signals (Sovizi & Aliannezhadi, 2022). The resonant conditions induce a distinct color change when AuNPs interact with the target analytes, which are then visually detected. Furthermore, owing to their unique optical properties in the visible region of the electromagnetic spectrum, AuNPs-based colorimetric sensors are a low-cost alternative to traditional analytical techniques, requiring only basic optical equipment. The high surface-to-volume ratio of AuNPs allows for surface functionalization to enhance sensitivity and selectivity (Baranwal et al., 2016; Marin et al., 2021). Colorimetric sensors based on AuNPs are capable of detecting mycotoxins in the low ppb (μg/kg) range, which is relevant to regulatory limits reported for several major mycotoxins in selected food products (Afsah-Hejri et al., 2012; Afsah-Hejri et al., 2013)..

Compared to traditional methods, nanoplasmonic sensors offer advantages, such as portability, fast response, minimal sample preparation, and the potential for multiplexed detection (Fan et al., 2024). The complementary use of LSPR-based colorimetric sensing for rapid screening and SERS for sensitive, molecular-level identification positions plasmonic sensors as versatile, future tools for food safety monitoring. In this review, both techniques are considered core plasmonic sensing strategies. However, they are discussed with complementary emphasis: LSPR is mainly associated with rapid screening, and SERS with highly sensitive molecular identification.

Fig. 2 depicts the fundamental mechanisms underlying LSPR and SERS, which form the basis of most plasmonic sensing platforms reported in the literature. When light interacts with noble metal nanoparticles, it induces collective oscillations of conduction electrons at the nanoparticle surface, generating the LSPR effect characterized by strong absorption and scattering of light. Changes in the local refractive index or nanoparticle aggregation induced by analyte binding can shift the plasmon resonance band, enabling colorimetric or optical detection. In contrast, when analyte molecules are adsorbed near or onto the nanoparticle surface, localized electromagnetic "hot spots" are generated around the nanoparticles, significantly enhancing the Raman scattering signal of the analyte molecules. This phenomenon forms the basis of SERS, which enables highly sensitive molecular identification (Huang et al., 2022).

Several recent reviews have surveyed SERS and plasmonic approaches to food safety and contaminant monitoring. For example, Hassan et al. (2025) have summarized recent trends in smart SERS sensors integrating machine learning and on-field sampling strategies for a range of food hazards. Ma et al. (2025) have focused specifically on strategies for the simultaneous detection of multiple food contaminants using labeled and label-free SERS methods. Zhang et al. (2024) have reported an integrated quantitative SERS sensor that couples extraction and identification for multi-mycotoxin analysis, demonstrating an applied hybrid magnetic/polydopamine-AuNP design. Similarly, Liu

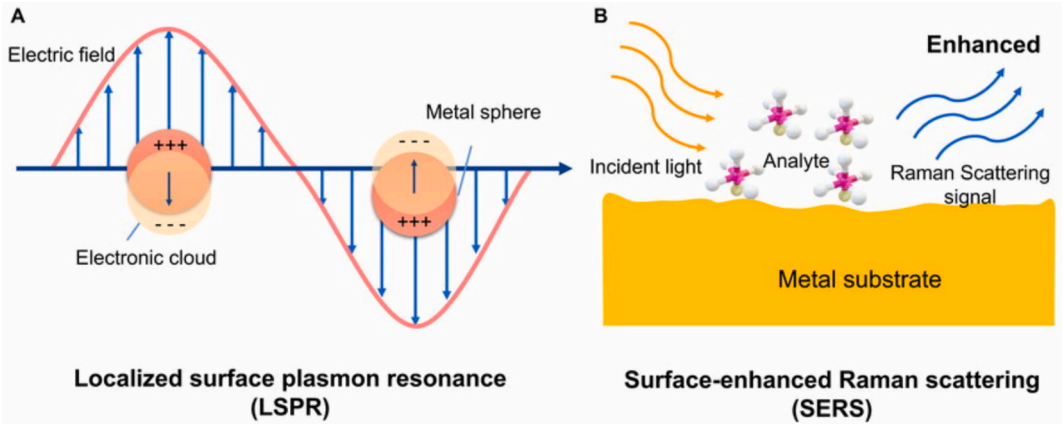

Fig. 2. Mechanism of localized surface plasmon resonance (LSPR) and surface-enhanced Raman scattering (SERS). Figure taken from Ref. (Huang et al., 2022).

et al. (2025) have systematically analyzed nanostructure-sensitized SERS substrates designed to improve analytical sensitivity in food safety applications, highlighting key challenges related to reproducibility of fabrication, signal stability, and performance in complex food matrices. Together with foundational surveys of SERS substrates for food analysis, these studies provide broad coverage of SERS substrate design, multiplexing strategies, and real-sample applications.

However, limited attention has been given to the role of naturally derived ligands in the functionalization of AuNP-based plasmonic nanosensors for mycotoxin detection. Therefore, this review focuses specifically on natural ligand–functionalized AuNP sensing platforms, highlighting their synthesis strategies, sensing mechanisms, analytical performance, and potential for sustainable food safety monitoring.

1. Green synthesis of AuNPs using natural and plant-derived ligands

Building on the plasmonic principles discussed in the previous section, the synthesis and surface functionalization of AuNPs are crucial to the analytical performance of plasmonic nanosensors. The transition from conventional AuNP synthesis to more sustainable, plant-based alternatives is important for the development of sustainable plasmonic sensors. Conventional synthesis requires strong chemical reducing agents, such as sodium borohydride, hydrazine, and citrate (Fahim et al., 2024). By contrast, plant-based synthesis requires a plant extract rich in bioactive compounds that can act as reducing and capping agents (Singh, Desimone, et al., 2023). Thus, plant-based synthesis has the advantages of biocompatibility, biodegradability, and eco-safety, consistent with green chemistry principles and sustainability (El-Deen & Hussain, 2025). In this review, the term "green synthesis" refers specifically to the use of plant extracts, amino acids, and naturally derived metabolites as reducing and stabilizing agents for AuNP synthesis, rather than microbial systems or purely synthetic bio-inspired molecules. Various plant-derived ligands, including flavonoids, phenolic acids, amino acids, and proteins, have been used to synthesize and stabilize AuNPs (Amina & Guo, 2020). Biomolecules possess reactive functional groups, including hydroxyl (–OH), carboxyl (–COOH), carbonyl (C=O), and amine ($–NH_2$). These functional groups are necessary for reducing Au^{3+} ions to neutral, metallic Au^0. The functional groups cap the nanoparticles and stabilize them in solution (Chen et al., 2020; Tsalsabila et al., 2022). In addition, they also help mediate the physicochemical properties of the nanoparticles, including their size, morphology, degree of dispersion, and stability, which determine their plasmonic sensing applications.

The plasmonic performance of ligand-functionalized AuNPs is strongly dependent on nanoparticle size, morphology, and surface chemistry. These properties are governed by the way natural ligands interact with the AuNP surface, including binding mode, surface coverage, packing density, and the ability to stabilize the nanoparticle interface. Smaller spherical AuNPs (<20–30 nm) typically exhibit sharp and symmetric LSPR bands with high colloidal stability. In contrast, larger or anisotropic structures (e.g., nanorods and nanostars) display tunable plasmon resonances that extend into the near-infrared region, enhancing electromagnetic field localization and SERS activity (Jeon et al., 2019).

Natural ligands influence nucleation kinetics and growth pathways, indirectly controlling particle size and morphology during green synthesis. Furthermore, ligand density and surface charge (zeta potential) govern interparticle spacing and aggregation behavior, which directly affect plasmon coupling efficiency and colorimetric sensitivity (S. Wang et al., 2026). Therefore, understanding ligand packing, orientation, and binding strength is critical for achieving reproducible sensing performance (Heuer-Jungemann et al., 2019). These parameters directly influence plasmonic signal intensity, spectral shift behavior, and SERS hotspot formation, which ultimately determine sensor sensitivity.

Functionalizing AuNPs with plant-based ligands provides a dual benefit: it supports sustainable, green synthesis and improves sensor performance. These ligands have several advantages for sensing applications, including enhanced size uniformity, colloidal stability, surface reactivity, and biocompatibility. The chemical structures of many natural ligands also enable the selective recognition of target analytes, making them ideal for bioanalytical applications. However, plant-derived ligands may exhibit compositional variability depending on extraction conditions, which can influence nanoparticle stabilization and sensing reproducibility. Therefore, natural ligand-based plasmonic nanosensors represent a promising eco-friendly strategy for mycotoxin detection, with growing potential for application in complex food matrices. Table 1 summarizes selected examples of plant-based ligands employed in the green synthesis of AuNPs, together with their main functional groups and functional roles in enhancing nanoparticle stability, selectivity, and sensing performance.

3. Ligand–toxin interactions and plasmonic signal generation

This section provides a mechanistic analysis of how ligand functionalization strategies influ-ence AuNP stability, ligand orientation, analyte recognition, and plasmonic sensing performance. Surface functionalization is crucial for enhancing the physicochemical properties of AuNPs for mycotoxin detection. Three main functionalization strategies are available: covalent, non-covalent, and hybrid.

Covalent functionalization involves chemical bonding between the ligand and the surface of AuNPs through thiol (–SH), carboxyl (–COOH), or amine ($–NH_2$) groups. Of these, thiol groups exhibit the highest affinity toward gold and yield well-defined Au—S bonds, which increase sensor robustness, allowing the sensor to withstand more aggressive conditions (Chen et al., 2020; Kato et al., 2023). This configuration enhances the quality of ligand orientation, decreases any chance of desorption, especially in complex food matrices, and allows for metabolite modifications (esterification or amination) to further improve binding efficacy and molecular recognition (Acres et al., 2014).

By contrast, non-covalent functionalization relies primarily on transient molecular interactions, including hydrogen bonding, electrostatics, and van der Waals interactions (Martinez-Gonzalez et al., 2017). The overall system stability is lower than that achieved with covalent functionalization because it relies on weak reversible interactions; however, this approach is useful for dynamic or stimuli-responsive sensors. Thus, non-covalent functionalization is particularly useful in dynamic or stimuli-responsive sensing systems, where sensor behavior changes in response to environmental factors such as pH, temperature, or ionic strength. (e.g., pH, temperature, or ionic strength) (Hatai et al., 2020; Ramachandran et al., 2024). Many types of non-covalent interactions can contribute to mechanisms for pre-concentration and/or elution for sensor development involving AuNPs.

Self-assembled monolayers (SAMs)—usually thiolated ligands—provide reliable stabilization for orienting ligands and allowing access to their intended analyte. SAMs provide enhanced solubilization, reproducibility, and colloidal stability, and have been used combined with AuNPs for detecting various biological targets, including viruses and toxins (Anh et al., 2022; Zhang, Chen, et al., 2023).

Furthermore, hybrid functionalization typically relies on polymers or lipids that are spontaneously functionalized onto AuNPs and allow for multi-functionality. For example, Hu et al. (2010) used PLGA–lipid–PEG systems to achieve higher biocompatibility, chemical and thermal stability, and multiplexing usability.

4. Plasmonic AuNP–mycotoxin interaction mechanisms

The sensing mechanism of metabolite-functionalized AuNPs relies on specific molecular binding and interactions between the functionalized ligand layer on the AuNPs and the target mycotoxin. Electrostatic attraction, hydrogen bonding, π–π stacking, and/or hydrophobic interactions may be involved, depending on the functional groups of the ligand and the structure of the mycotoxin (Ramachandran et al., 2024).

Table 1
Selected examples of plant-based ligands used for the green synthesis of AuNPs and their functional roles in analyte detection.

Ligand/plant extract	Plant source	Main functional groups	Role in AuNP synthesis	Detection benefits	Sources
Quercetin	Fruits, vegetables	–OH, C=O	Stabilizer and reducing agent	Eco-friendly synthesis, biocompatibility, high selectivity, and sensor stability	(Huang et al., 2023)
Gallic acid	Tea	–OH, –COOH	Reducing and capping agent and stabilizer	Promotes uniform AuNP size and high stability	(Farzaneh et al., 2024)
Catechin	Green tea	–OH	Reducing agent and selective binding ligand	Improved selectivity	(Serdar et al., 2025)
Curcumin	Turmeric	–OH, C=O, $–OCH_3$	Reducing and capping agent and stabilizer	Biocompatible, provides high selectivity, and increases stability	(Ghoniem et al., 2024)
Ascorbic acid	Citrus fruits	–OH	Reducing agent, surfactant, and stabilizer	Promotes small AuNP formation	(Heuer-Jungemann et al., 2019)
Arginine	Protein hydrolysates	$–NH_2$, –COOH	Electrostatic stabilizer; promotes binding specificity	Strong interaction	(Bolat et al., 2025)

For example, polyphenolic ligands, such as curcumin, stabilize AuNPs through hydroxyl or diketone groups, π-conjugated systems, or hydrogen donors to promote selective binding to mycotoxins like aflatoxins and ochratoxins. AuNP aggregation or changes to the surface environment are observed when such ligands bind or induce the binding of mycotoxins. The changes in the AuNPs may be reflected in optical signal shifts in LSPR or color modifications that can be visualized with the naked eye (Chen et al., 2020).

Furthermore, some ligands induce target-specific aggregation based on their binding to the mycotoxins, and produce corresponding shifts in the color of AuNPs (e.g., from red to blue), so that readout is rapid and visible. Furthermore, ligand bonding to mycotoxins leads to changes in electron density on the surface of AuNPs and modulation of plasmonic resonance, which enhances SERS signals. As shown in Fig. 3, purpurin molecules covalently attach to the AuNP surface through Au—O coordination bonds (covalent). By contrast, AFB1 is captured via hydrogen bonding (non-covalent), together enabling the selective recognition and modulation of the plasmonic response.

Hydrogen bonding between the hydroxyl groups of plant-derived metabolites and the oxygen atoms in mycotoxins provides an initial anchoring mechanism for molecular recognition. However, the strength of this interaction depends on the binding affinity and structural features of the toxin, particularly the density of hydrogen-bond acceptors, such as carbonyl and lactone groups. Consequently, more polar mycotoxins, including AFB1 and OTA, often exhibit higher stabilization energies than less functionalized analogs (Liu, Lao, et al., 2024). Despite this advantage, achieving high selectivity in food matrices remains challenging, as competing nucleophiles and proteins can disrupt these noncovalent interactions (Rodriguez-Quijada et al., 2020). Although reversible hydrogen bonding enables rapid sensing, matrix components may compete with toxins for ligand-binding sites, potentially reducing sensitivity when the ligand density is not sufficiently optimized (Atanasova-Penichon et al., 2016).

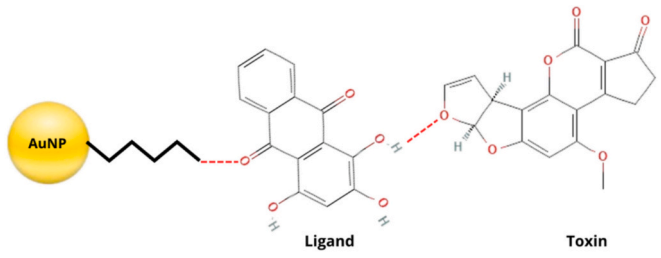

Fig. 3. Schematic illustration of purpurin as a ligand functionalizing gold nanoparticles (purpurin–AuNPs) interacting with aflatoxin B1 (AFB1; mycotoxin). Purpurin molecules are attached onto the AuNP surface through Au—O coordination bonds (via carbonyl oxygen groups), while AFB1 is captured via hydrogen bonding. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.1. Kinetic stability and the risk of non-specific aggregation

The challenge in translating AuNP-based LSPR sensors from buffer solutions to real-world food extracts is distinguishing between analyte-induced aggregation and matrix-induced instability. Standard food extraction protocols often result in high ionic strength or extreme pH shifts in the final assay medium. Usually, an increase in ionic strength can screen the electrostatic repulsive forces (zeta potential) provided by the natural ligands, leading to charge neutralization and subsequent non-specific aggregation (X. Zhang et al., 2020). This kinetic process results in a bathochromic LSPR shift that is indistinguishable from a positive mycotoxin detection, leading to potential false positives.

Therefore, it is essential to evaluate the Derjaguin–Landau–Verwey–Overbeek (DLVO) theory stability of natural ligand–functionalized AuNPs (Phan & Haes, 2019). Although plant-derived metabolites can provide steric stabilization, their effectiveness may be compromised in acidic food matrices (e.g., fruit juices and fermented grains), where protonation of functional groups, such as carboxylates, reduces the surface charge responsible for electrostatic stabilization (Selmani et al., 2023). Consequently, future high-impact studies should incorporate matrix-blank kinetic controls to confirm that the observed LSPR response originates from specific ligand–toxin electronic interactions rather than nonspecific nanoparticle aggregation induced by the ionic environment of the sample. Such controls are essential for evaluating matrix interference tolerance and determining whether these sensing platforms can maintain reliable performance in complex food extracts.

5. Application in mycotoxin detection: case examples

Plant-based ligands can be used to functionalize AuNPs, offering a promising route toward the development of next-generation plasmonic nanosensors with enhanced tunability and potential for on-site mycotoxin detection. Although this review primarily focuses on natural ligand–functionalized AuNP systems, studies that employ natural ligands as direct recognition elements for mycotoxins remain relatively limited. Accordingly, the examples discussed in this section include both natural ligand–based systems and selected hybrid platforms incorporating antibodies or aptamers for comparative purposes. These hybrid systems are included as performance benchmarks to highlight current analytical capabilities and clarify the differences between conventional bioreceptor-based platforms and emerging natural ligand–based approaches. Table 2 summarizes the examples, which are grouped by the individual mycotoxins and give the type of ligand used (e.g., antibodies, aptamers, and plant-based ligands), mode of detection (e.g., colorimetric, SERS, and imaging surface plasmon resonance (iSPR)), limit of detection (LOD), food matrix, selectivity, total response time, and whether the AuNP sensor is portable. Grouping the content by mycotoxin facilitates the comparison of sensor performance in terms of analytical sensitivity, assay speed, and application to food samples.

Table 2
Summary of AuNP-based mycotoxin nanosensors using natural or hybrid ligands.

Mycotoxin	Ligand Type	Detection Mode	LOD (ng/mL)	Food Matrix	Selectivity / Interference	Time to Result	Field Deployable	Reference
AFB1	Plant-extract modified silica–AuNPs	Colorimetric	0.16	Maize, Peanuts	High selectivity vs OTA and ZEN	~15 min	Yes	(Althagafi et al., 2021)
OTA	Aptamer–AuNPs (hybrid with natural base)	SERS	1.43	Wheat	High selectivity toward OTA	~30 min	Potentially	(J. Sun et al., 2021)
ZEN	HRP-functionalized AuNPs (natural enzyme)	Colorimetric	0.08	Grain	Minimal interference from DON	<20 min	Yes	(S. Sun & Xie, 2021)
FB1	Antibody–AuNPs	ICTS	3.27	Maize	High selectivity	~10 min	Yes (strip-based)	(Y. Wu et al., 2020)
T-2 Toxin	Aptamer–AuNPs	SERS	0.0056	Wheat and Maize (Corn)	High Selectivity vs. AFB1, OTA, ZEN, and DON	30–45 min	Yes	(Khan et al., 2023)
CPA	anti-CPA antibodies	iSPR	0.42	Maize	High, minimal cross reactivity	15–20 min	Potentially	(Hossain et al., 2019)

5.1. *Aflatoxin B1*

Aflatoxin B1 is a highly toxic mycotoxin produced by *Aspergillus* species and commonly detected in cereals, peanuts, and other nut-based products. Althagafi et al. (2021) have developed a colorimetric immunoassay using gold-decorated mesoporous silica nanoparticles functionalized with anti-AFB1 antibodies. In this system, antibody–antigen binding induces aggregation of AuNPs, causing a LSPR shift that produces a visible color change from pink to violet. The assay achieved a low detection limit of 0.16 ng/mL and demonstrated high selectivity toward AFB1 in maize and peanut samples, with analysis times of 10–30 min. While this platform enables rapid, visually interpretable detection suitable for field screening, molecular recognition is primarily governed by antibodies. The plant-derived components primarily contribute to nanoparticle synthesis and stabilization. This highlights the current reliance on biological receptors and the limited development of natural ligand–AuNP systems for direct mycotoxin recognition.

5.2. *Ochratoxin A*

Ochratoxin A is a nephrotoxic mycotoxin commonly detected in cereals, coffee, and dried fruits. Sun et al. (2021) have developed a SERS aptasensor using AuNPs functionalized with OTA-specific DNA aptamers. In this system, aptamer–OTA binding localizes the toxin near the plasmonic surface, enhancing the Raman signal and enabling sensitive detection. The sensor achieved a detection limit of 1.43 ng/mL in wheat samples and produced results within approxi-mately 30 min. While aptamers provide strong molecular recognition and improved stability compared with antibodies, their performance can be influenced by environmental conditions, such as ionic strength and pH. In this platform, the natural molecules on the nanoparticle surface con-tributed to improved colloidal stability and SERS performance, illustrating how natural ligands can support hybrid sensing systems. However, as in many plasmonic mycotoxin sensors, toxin recogni-tion is still primarily governed by the aptamer rather than the natural ligand..

5.3. *Zearalenone*

Zearalenone (ZEN) is an estrogenic mycotoxin produced by Fusarium species and commonly detected in maize, wheat, and vegetable oils. S. Sun and Xie (2021) have developed a colorimetric aptasensor using AuNPs functionalized with horseradish peroxidase (HRP) for rapid ZEN detec-tion. In this system, HRP provides catalytic signal amplification while the aptamer enables selective recognition of ZEN, inducing measurable optical changes in the AuNP system. The assay achieved an ultra-low detection limit of 0.08 ng/mL. It showed high selectivity, with minimal interference from other toxins, such as deoxynivalenol (DON), in spiked corn oil samples within 30 min. While enzyme-assisted platforms enable high analytical sensitivity, the enzyme stability may be affected by storage and environmental conditions (Khumngern & Jeerapan, 2024; J. Zhang et al., 2022). Moreover, as with many plasmonic sensing strategies, toxin recognition relies primarily on the aptamer–enzyme system, whereas the natural ligands primarily contribute to nanoparticle stabi-lization. This highlights the potential of exploring natural ligand–toxin interactions to develop sim-pler and more sustainable AuNP-based sensing platforms.

5.4. *Fumonisin B1*

Fumonisin B1 (FB1) is a mycotoxin predominantly associated with maize and maize-derived products known to cause liver and kidney toxicity. Wu et al. (2020) have developed a multicolor immunochromatographic test strip using shape-engineered AuNPs functionalized with anti-FB1 antibodies for visual detection. In this system, AuNPs labels generate distinct colorimetric signals on the test strip, enabling rapid identification of FB1 through antibody–antigen recognition. The assay achieved a detection limit of 3.27 ng/mL in maize samples and demonstrated high selectivity against other mycotoxins, with results visible to the naked eye within approximately 12 min. While AuNP-based lateral flow assays offer advantages such as rapid response, portability, and minimal instrumentation, their dependence on antibodies may increase production costs and raise stability concerns under varying environmental conditions. (Hosseini et al., 2020; Kinyua et al., 2025; S. Sun & Xie, 2021). Exploring natural ligand–AuNP interactions could provide an alterna-tive strategy to develop simpler, more sustainable plasmonic sensors for fumonisin detection..

5.5. *T-2 toxin*

T-2 toxin is a highly toxic trichothecene mycotoxin commonly detected in cereal grains. Khan et al. (2023) have developed a SERS-based aptasensor using AuNPs functionalized with a T-2-specific DNA aptamer. In this system, aptamer–toxin binding localizes T-2 molecules near the plasmonic surface, enhancing the Raman signal and enabling highly sensitive detection. The sensor achieved an ultra-low detection limit of 0.0056 ng/mL. It demonstrated strong selectivity against other mycotoxins, including AFB1, OTA, ZEN, and DON, in wheat and maize samples with analysis times of 30 to 45 min. While aptamer-assisted SERS platforms offer exceptional analytical sensitivity, their fabrication often requires precise nanoparticle functionalization and controlled surface chemistry.

5.6. *A-cyclopiazonic acid*

α-Cyclopiazonic acid (CPA) is a mycotoxin commonly associated with maize and cheese con-taminated with Aspergillus and Penicillium species. Hossain et al. (2019) have presented an iSPR immunoassay using AuNPs conjugated with anti-CPA antibodies. In this system, antibody–antigen interactions induce changes in the local refractive index near the AuNP surface, generating a meas-urable plasmonic signal. The

assay achieved a detection limit of 0.42 ng/mL in spiked maize sam-ples. It demonstrated high selectivity with minimal cross-reactivity toward potential interfering compounds, strong matrix tolerance, and good reproducibility, with analysis times of approximate-ly 15–20 min. This sensing platform could potentially be adapted for field deployment using portable iSPR instrumentation; however, sample preparation relies on conventional solvent-based extraction procedures. While iSPR platforms provide excellent analytical sensitivity, the require-ment for specialized instrumentation may limit portability compared with colorimetric or lateral flow assays. Consequently, although highly effective for laboratory analysis, simpler ligand-based plasmonic sensors may be more suitable for rapid on-site mycotoxin screening.

Overall, the case studies summarized in Table 2 demonstrate that AuNP-based plasmonic sensors can achieve detection limits in the low ng/mL range with rapid response times suitable for screening applications. However, analytical sensitivity alone does not determine practical utility, as selectivity in complex food matrices, fabrication complexity, cost, and field robustness are equally important for real-world deployment. In addition, validation parameters, such as accuracy, precision, reproducibility, and robustness, should be reported more systematically, as many studies emphasize low detection limits but provide limited evaluation of repeatability, recovery, and performance consistency across batches or under variable sample conditions. Similarly, recovery percentages in real or spiked food samples should be reported more consistently, as they are essential for evaluating matrix tolerance and the practical analytical accuracy of plasmonic nanosensors. Aptamer-based SERS sensors generally provide the highest sensitivity due to strong molecular recognition and signal amplification, while antibody-based systems remain widely used because of their high specificity and compatibility with lateral flow formats (Khlebtsov et al., 2019).

However, studies employing purely natural ligand–functionalized AuNPs remain scarce. In most reported systems, natural molecules act as reducing or stabilizing agents rather than direct toxin-recognition elements. Expanding the role of plant-derived metabolites and small biomolecules as functional ligands could enable more sustainable and cost-effective plasmonic sensing strategies. At present, AuNPs-based sensors are best considered rapid screening tools that complement conventional analytical techniques such as HPLC or ELISA (Khlebtsov et al., 2019; J. Singh & Mehta, 2020). The general sensing strategies employed in natural ligand–based AuNP plasmonic platforms, including colorimetric LSPR sensing and SERS-based detection, are illustrated in Fig. 4.

Although natural ligand–based systems offer advantages in sustainability, cost reduction, and biocompatibility, their binding affinity may be lower than that of antibody- or aptamer-based platforms. Nevertheless, several studies have reported detection limits in the low ng/mL range, demonstrating competitive analytical sensitivity. For instance, L-lysine–functionalized AuNPs achieved an LOD of 4.18 ng/mL for aflatoxin B1 (Sánchez-Carrillo et al., 2024), compared with 0.15 ng/mL for an antibody-functionalized system (Sharma et al., 2024). While antibodies typically exhibit higher affinity, the difference in performance is not always substantial, indicating that sensitivity depends not only on ligand chemistry but also on nanoparticle architecture and interfacial plasmonic interactions. In addition, natural ligands may offer advantages in terms of greener preparation and potentially simpler storage conditions. Antibody-based systems often show lower environmental stability and shorter shelf life, while aptamer-based systems generally provide better chemical stability but still require carefully controlled assay conditions. Thus, natural ligands represent a viable and sustainable alternative sensing strategy.

6. Trends in on-site and portable sensing platforms

The growing need for rapid, accurate, and decentralized detection of mycotoxins has spurred the development of portable, on-site sensing platforms with sufficient speed, sensitivity, and usability. This is especially important for resource- and labor-constrained regions or difficult-to-access locations (Lee et al., 2023; Mohanta & Pandey, 2023; Yi & Xianyu, 2023). Current de-velopments have mainly focused on paper-based analytical devices (PADs), smartphone assays, microfluidics lab-on-chip technology, and hybrid plasmonic biosensors, many of which are now commercialized (Laza et al., 2024; Liu, Zhang, et al., 2024). Among them, the paper-based lateral flow immunoassay (LFIA) is the most developed format. This method offers low cost, ease of use, and detection times of less than 30 min using AuNP-based readings (i.e., colorimetric readouts) (Khlebtsov et al., 2019; Li, Wang, et al., 2023). Multiplexed immunochromatographic strips can detect up to 15 mycotoxins simultaneously, with recovery rates greater than 90% and strong correlation to LC-MS/MS results (Zhou et al., 2024). Additionally, metabolite-AuNPs exhibit increased selectivi-ty, stability, and biocompatibility. Catechin, tyrosine, and hematoxylin ligands enable the naked-eye detection of mycotoxins through the formation of aggregates or changes in LSPR upon their addition (Pinheiro et al., 2021; Yi & Xianyu, 2023).

Smartphone integration has transformed PADs and portable biosensors into connected diagnostic tools. Device cameras can capture LSPR-induced colorimetric or fluorescence changes, which are

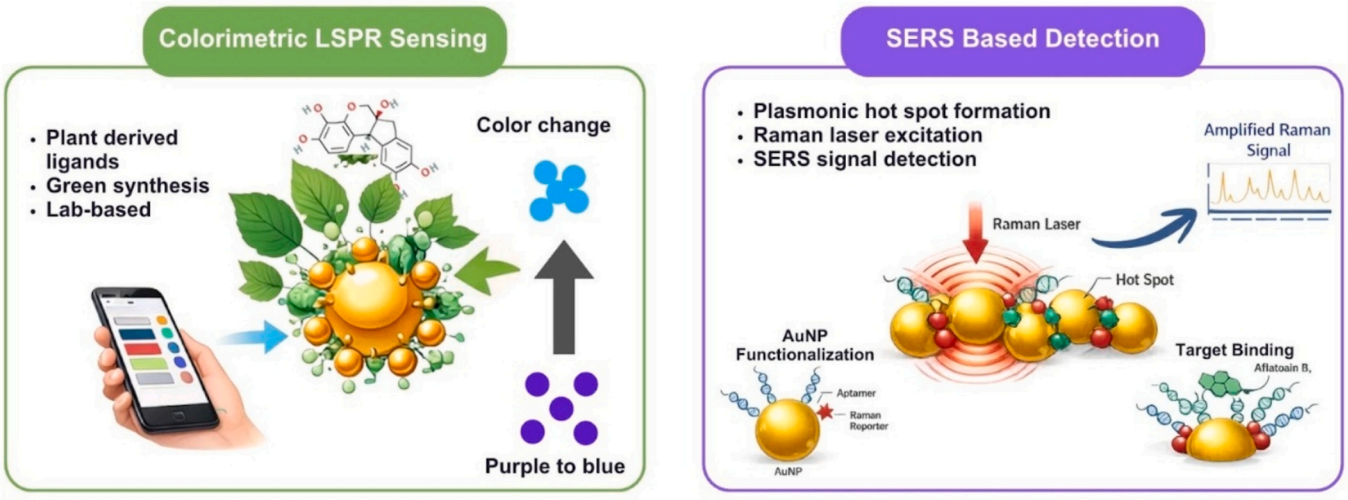

Fig. 4. Schematic representation of natural ligand-functionalized AuNP plasmonic sensing strategies for mycotoxin detection, including colorimetric LSPR-based aggregation sensing and SERS-based signal amplification.

processed by dedicated apps to yield quantitative results, real-time data sharing, and GPS-enabled traceability (Li, Li, et al., 2023; Dillon & Campbell, 2023; Zhang, Zhou, et al., 2023). In practical food analysis, PAD-based assays typically have simple sample preparation steps, such as solvent extraction or dilution, to reduce interference from complex food matrices containing proteins, pigments, and lipids (Zhang, Chen, et al., 2023). Although many AuNP-based PAD sensors are described as label-free systems, the nonspecific adsorption of matrix components can influence nanoparticle aggregation and affect signal reliability (Masson, 2020; Zhang, Zhou, et al., 2023). Nevertheless, when applied to spiked food samples, these sensors generally report acceptable analytical recoveries in the range of approximately 80%–110%, supporting their suitability for rapid on-site screening applications (Zhou et al., 2024). Notable examples include smartphone-based aptasensors for ZEN detection in maize with visual limits of 5 ng/mL (Zhang, Zhou, et al., 2023) and nanoenzyme-mediated LFIAs for simultaneous mycotoxin detection in aqueous samples (Li, Li, et al., 2023). However, quantitative analysis using smartphone cameras may be affected by external factors such as lighting conditions, background color variations, and matrix-induced signal interference, which require calibration algorithms or controlled imaging environments to ensure reliable measurements (Dillon & Campbell, 2023; Li, Wang, et al., 2023).

Microfluidic lab-on-a-chip platforms (especially those produced by 3D printing) can integrate sample pretreatment, reaction thermoregulation, and detection into a single platform, enabling steps such as filtration, dilution, or analyte enrichment to reduce matrix interference and improve analytical reliability when analyzing complex food samples (Tong et al., 2023; F. Wu et al., 2022). For example, Fernandez Solis et al. (2024) have reported that PMMA-deposited electrochemical chips with reduced graphene oxide–nanoporous gold electrodes achieved ten-fold lower T-2 toxin detection limits than ELISA. Moreover, dual-mode (colorimetric/fluorescent) aptasensors printed in 3D on paper with smartphone readouts have achieved a sensitivity of 0.13 ng/mL for sulfdimethoxine in food samples (Khachornsakkul et al., 2025).

Portable sensors based on plasmonic phenomena (e.g., AuNP or AgNP LSPR effects) can provide detection capabilities at lower limits and even enable label-free detection in some instances (Masson, 2020; Y. Wu et al., 2020). The selectivity and stability of these detectors can be improved by incorporating small molecules, amino acids, or fatty acids as functional ligands. Newer designs tend to integrate these sensors into microfluidic chips, PADs, and smartphone-based tools (R. Pang et al., 2022; Selvam & Al-Humairi, 2023). These platforms can also be integrated into IoT frameworks, enabling remote detection, cloud-based data storage, and real-time notifications of contamination events (Selvam & Al-Humairi, 2023). However, for real-world deployment, long-term environmental stability and storage conditions must also be considered, as factors such as nanoparticle aggregation, temperature fluctuations, and humidity may influence sensor performance during storage or transportation (Masson, 2020; Singh, Dutt, et al., 2023). Therefore, further efforts are needed to improve sensor shelf life and ensure consistent analytical performance under practical field conditions.

Overall, the convergence of inexpensive substrates, plasmonic nanomaterials, smartphone analytics, and rapid prototyping is forcing a shift away from laboratory assays to field-deployable, multiplexed, and connected diagnostic platforms. These advances are expected to revolutionize mycotoxin surveillance and facilitate the rapid, reliable, and accessible detection of mycotoxins throughout agricultural and food supply chains (Lee et al., 2023; Liu, Zhang, et al., 2024).

7. Challenges and future outlook

Nanoplasmonic sensors demonstrate excellent analytical performance; however, their translation from laboratory prototypes to market-ready technologies remains constrained by technical, regulatory, and manufacturing challenges (Jadhav et al., 2024; Yang & Duncan, 2021). Major barriers include high production costs, limited standardization, and difficulties in maintaining consistent sensitivity and portability in field-deployable platforms (Kurabayashi & Park, 2023). Although plant-mediated green synthesis offers an environmentally friendly approach to AuNP production, it poses reproducibility challenges because plant extracts contain complex mixtures of biomolecules, such as polyphenols, flavonoids, and organic acids. Variations in plant species, geographical origin, seasonal conditions, and extraction methods can influence nanoparticle nucleation, growth, and surface stabilization, leading to inconsistent particle size and plasmonic responses (Abegunde et al., 2024; Dubey et al., 2023). One promising strategy to improve standardization is the use of purified natural metabolites (e.g., quercetin or gallic acid), which preserve the advantages of natural ligands while enabling more controlled and reproducible AuNP synthesis (Hasmin et al., 2020). These challenges collectively represent major commercialization barriers, limiting the transition of green plasmonic nanosensors from proof-of-concept studies to standardized market-ready products.

Batch-to-batch variability in ligand functionalization remains a major barrier to the industrial translation of nanoplasmonic sensors, as differences in surface coverage and ligand orientation can compromise selectivity, reproducibility, and shelf life (Hasmin et al., 2020). Variations in surface chemistry may reduce colloidal stability and plasmonic performance, often causing nanoparticle aggregation or ligand desorption in poorly stabilized systems (Hasmin et al., 2020; Kennon & Niedermeyer, 2024). In contrast, formulations optimized using synergistic capping agents can achieve stability ranging from several months to years, underscoring the importance of accelerated stability testing for practical deployment (Kennon & Niedermeyer, 2024; L. Pang et al., 2024). Beyond technical challenges, regulatory approval remains another key hurdle. Although AuNPs are often considered biologically inert, regulatory agencies, such as the European Food Safety Authority (EFSA) and the U.S. Food and Drug Administration (FDA), require rigorous safety evaluations, including assessments of nanoparticle migration into food products (Jain et al., 2018; Parkinson, 2021). Furthermore, many studies rely on artificially spiked samples that may not fully reflect the complexity of food matrices. Future work should adopt standardized validation protocols using naturally contaminated reference materials and report key analytical parameters, such as accuracy, precision, and recovery, to facilitate regulatory acceptance and commercializa-tion.

Another conceptual challenge lies in the current reliance on hybrid biosensing systems that incorporate antibodies or aptamers, which may seem inconsistent with the sustainability-driven focus on natural ligand–functionalized sensors. While these biomolecular recognition elements offer high binding specificity, they often involve costly synthesis, complex immobilization procedures, and limited long-term stability (S. Sun & Xie, 2021; W. Zhang et al., 2021). As a result, many current platforms represent a transitional stage in sensor development. Emerging strategies increasing-ly explore biomimetic recognition elements, including molecularly imprinted polymers and struc-turally defined plant-derived metabolites, which can mimic the binding affinity of antibodies while maintaining advantages such as chemical robustness, lower cost, and improved stability (Chen et al., 2020; Ramachandran et al., 2024; Wen et al., 2023). Such approaches may represent a next-generation direction for plasmonic nanosensors, enabling the development of environmentally sus-tainable sensing platforms without compromising analytical performance.

Looking ahead, integrating nanoplasmonic sensors with IoT and blockchain infrastructures offers a promising pathway toward real-time and transparent food safety monitoring (Bhatlawande et al., 2024). When coupled with portable sensing platforms such as smartphone-based assays, IoT networks can enable continuous data transmission from field locations, allowing rapid detection and reporting of contamination events. However, the reliability of decentralized testing raises ques-tions regarding data integrity and user-dependent

variability. Blockchain technology offers a poten-tial solution by creating encrypted, immutable digital records of sensor outputs, enabling traceable "farm-to-fork" documentation of food safety data (Kim et al., 2018). Such distributed ledgers could enhance trust in on-site testing results by ensuring that sensor measurements, timestamps, and geo-location data cannot be altered after collection. Nevertheless, widespread implementation will require standardized data exchange protocols, cybersecurity safeguards, and interoperable regulatory frameworks to ensure that digitally recorded sensor data meets food safety compliance requirements.

Key next steps include:

- Developing internationally recognized green synthesis standards linked to regulatory compliance (Abegunde et al., 2024; Hasmin et al., 2020)
- Establishing statistical process control measures for ligand consistency
- Creating packaging and formulation strategies for extended shelf life (Kennon & Niedermeyer, 2024; L. Pang et al., 2024)
- Advancing regulatory science to define ENM categories, detection methods, and approval pathways (Hasmin et al., 2020)
- Designing interoperable IoT/blockchain platforms for traceable, cloud-connected food safety systems (Bhatlawande et al., 2024)

In the long run, achieving commercial-scale, standardized production coupled with digitally integrated monitoring systems will position nanoplasmonic sensors as a core technology in global food safety networks, bridging the gap between cutting-edge research and real-world impact.

8. Conclusion

The increasing demand for rapid, sensitive, and sustainable tools for mycotoxin detection in food has encouraged the development of plasmonic sensors based on AuNPs. This review summarizes emerging approaches that leverage the unique properties of AuNPs combined with natural and plant-based ligands to develop sustainable colorimetric and SERS sensors. AuNPs provide useful optical signal readouts for diverse toxicity assays. Furthermore, plant-based ligands offer structural specificity, eco-friendliness, and surface functionality for the selective binding of toxins.

Recent advances demonstrate the potential of AuNP-based sensors for detecting mycotoxins such as aflatoxin B1, ochratoxin A, zearalenone, and fumonisins, offering low detection limits and miniaturization potential. Plant-derived ligands bind mycotoxins via hydrogen bonding, π–π stacking, and electrostatic interactions, enhancing the localized surface plasmon resonance signal without labels or complex preparation. Furthermore, current trends toward portable formats, including paper dipstick sensors, smartphone readouts, and 3D-printed microfluidic chips, underscore a shift toward user-friendly, field-deployable diagnostics.

Nevertheless, challenges persist, including the need for standards for the green synthesis of ligands, the limited stability of this type of ligand, and the lack of appropriate regulatory frameworks for their application. Looking forward, we predict innovations coupling this technology with digital-based solutions (IoT and blockchain) for real-time monitoring systems to enhance food safety. AuNPs functionalized with metabolites represent a promising avenue for sustainable nanosensors with applications in food safety, agriculture, and public health.

CRediT authorship contribution statement

Siti Syahirah Amirah Mazelan: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Mohammad Norazmi Ahmad:** Writing – review & editing, Visualization, Supervision, Software, Resources. **Mohd Basyaruddin Abdul Rahman:** Writing – review & editing, Visualization, Supervision, Software, Resources. **Erna Normaya:** Writing – review & editing, Visualization, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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