A comprehensive review: Advancements in nanomaterials on the risk prevention, detection, and elimination of mycotoxin contamination

Lavanya Ganesan[1], Balamuralikrishnan Balasubramanian[2#*], Sri Kalpana Kumaravel[1], Viji Maluventhen[3], Maruthupandian Arumugan[1*]

[1]Department of Botany, Ethnopharmacology and Algal Biotechnology Laboratory, School of Life sciences, Periyar University, Salem, Tamil Nadu, India; [2]Department of Food Science and Biotechnology, College of Life Sciences, Sejong University, Seoul, South Korea; [3]Department of Botany, Thiagarajar College, Madurai, Tamil Nadu, India

[#]Contributed equally as first author

***Corresponding Authors:** Balasubramanian Balamuralikrishnan, Department of Food Science and Biotechnology, College of Life Sciences, Sejong University, Seoul 05006, South Korea. Email: bala.m.k@sejong.ac.kr; Arumugan Maruthupandian, Department of Botany, Ethnopharmacology and Algal Biotechnology Laboratory, School of Life Sciences, Periyar University, Salem-636 011, Tamil Nadu, India. Email: pandianmdu82@gmail.com

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Abstract

Mycotoxins are poison that filamentous fungi generate under specific conditions. Mycotoxins in food and feed have a detrimental effect on both human and animal health, resulting in significant financial losses for agriculture sector. Despite the continuing advancement of traditional approaches, modern research trends favor novel alternatives. Therefore, it is crucial to prevent mycotoxin contamination, which has raised concerns around the globe. Recent advancements in the management of mycotoxin contamination have been possible by the application of promising new nanomaterials. Mycotoxins have negative impacts on human health, but nanotechnology methods appear to be viable, efficient, and affordable solutions. This review elucidates information on the incidence and toxicology of mycotoxins. Nanotechnology's potential for removal of mycotoxins is mentioned briefly. Then, attention is directed on using newly developed nanomaterials to regulate mycotoxin contamination, such as testing, production, inhibition, adsorption, and removal of mycotoxins. The issues regarding the toxicity, incidence, and management of mycotoxins are tentatively presented along with potential prospects for using nanotechnology to remove mycotoxins from food and feed.

Keywords: mycotoxin types; mycotoxin detection; nanomaterials; mycotoxin control; mycotoxin risk elimination

Introduction

Mycotoxins are toxic substances that are synthesized by fungus under particular circumstances, which include elevated levels of moisture, presence of tainted or substandard crops, and inadequate agricultural techniques (Abdallah *et al.*, 2024). These toxins are secondary metabolites and possess low molecular weight. Several studies have emphasized the synthesis of mycotoxins by filamentous fungus (Bennett, 1987; Horky *et al.*, 2018). Nevertheless, the existence of filament on grains does not always imply the existence of mycotoxins. However, there is a potential for mycotoxin synthesis. It is crucial to acknowledge that the lack of molds on stored food and feed over an extended period does not guarantee that the grain is devoid of mycotoxins (Edwards, 2004;

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Simpson *et al.*, 2001). Over 500 types of mycotoxins are documented and about 10,000 different varieties of fungus are identified. It is conceived that over 1,000 additional species are yet to be discovered. No recognized systematic technique exists for detecting masked mycotoxins, thus making their identification an exceptional problem (Dallasta *et al.*, 2015; Haque *et al.*, 2020). Foods and feeds consisting of mycotoxins present a substantial global health risk due to their potential to harm humans and animals severely. This can result in various health issues, such as damage to the liver, heart, kidneys, gastrointestinal tract, and even the development of cancer, ultimately leading to death (Freire and Santana, 2018; Khaneghah *et al.*, 2019).

In Malaysia, India, and Kenya, severe outbreaks of aflatoxicosis are observed that resulted in innumerable deaths of people (Yang *et al.*, 2020a). The topic of mycotoxin risk is complex and needs attention from both agricultural technology industry and scientific community as a whole. Several types of fungi, such as Aspergillus, Fusarium, Claviceps, and Alternaria, produce mycotoxins. Aspergillus generates aflatoxins (AFT), ochratoxin A (OTA), trichothecenes (TCTs) and deoxynivalenol (DON) whereas Fusarium produces zearalenone (ZEN), fumonisins (FUMs) B1 and B2 as well as emerging mycotoxins, such fusaproliferin (FUs), moniliformin, beauvericin (BEA), and enniatins (ENNs). Meanwhile, Claviceps creates ergot alkaloids (EAs), while Alternaria produces altenuene, alternariol, alternariol methyl ether, altertoxin, and tenuazonic acid (Cunha *et al.*, 2018). Certain mycotoxins are more prevalent than others, such as AFT, ZEA, OTA, FUM, PAT, and TCT. The mycotoxins mentioned in the study conducted by Haque *et al.* (2020) and Luo *et al.* (2018) are a significant cause for worry in both food sector and public health. The persistent and substantial issue of mycotoxin contamination of foods and feeds has prompted global outrage. Additionally, FUM has been known to cause toxic effects in livestock, which causes pneumothorax enlargement in pigs, hydrothorax, porcine respiratory edema syndrome, and equine leukoencephalomalacia (ELEM) in horses (Agriopoulou *et al.*, 2020). This problem is unpredictable and uncontrollable and can crop up at any point in food production, such as pre-harvest, during harvest, drying, or storage. This can put consumers at risk of being directly exposed to mycotoxins through food products or indirectly through feed (Winter and Pereg, 2019).

Getting rid of mycotoxins during food production and processing can be difficult due to their resistance to chemical and physical treatments as well as thermal processes (Alshannaq and Yu, 2017; Marin *et al.*, 2013). Besides, the presence of mycotoxins in the food and feed supply is a significant challenge in their removal, as they exhibit long-lasting toxicity (Laan *et al.*, 2006; Luo *et al.*, 2018). Numerous methods are available to control mycotoxin contamination, which primarily rely on two approaches—techniques for pre-harvesting protection and post-harvesting mycotoxin removal. These methods are studied and developed extensively (Ben Taheur, 2019). The most effective method for preventing mycotoxin production is through pre-harvest prevention strategies, such as implementing good agricultural and manufacturing practices. However, if mycotoxin contamination does occur, it becomes crucial to detect and detoxify them post-harvest. This was emphasized by Anfossi *et al.* (2016), Chauhan *et al.* (2016), and Jard *et al.* (2011). Proper management of crops is crucial in preventing the occurrence of mycotoxins. Negative factors that could affect the spread of mycotoxins during the growth period include drought, insect infestations, changes in temperature, and crop rotation, as stated by Osweiler (2000). According to Cheat and Oswald (2016), mycotoxins generated by mold have harmful effects on animals, such as poultry, being the most vulnerable, followed by pigs and ruminants. It is widely known that ruminants have a high ability to metabolize certain types of mycotoxins with an efficiency rate of almost 100% (Rodrigues, 2014). These mycotoxins are often lipophilic and are present in animal products. This can lead to health issues, such as the presence of AFL M1 in milk, which has been linked to serious health issues (Aslam *et al.*, 2016).

Various adsorbents are used as nutritional supplements, resulting in recent developments in removal of mycotoxins from food and feed. Owing to their opposing polarity, the most often used fragments of clay are bentonites and zeolites (Dal Pozzo *et al.*, 2016). A potential issue with clay absorbents is their propensity to bind to feed-borne vitamins and minerals. Mycotoxins are a notable problem discovered in many fields, such as veterinary sciences, mycology, plant science, analytical and applied chemistry, toxicology, food science, and agriculture.

Mycotoxin contamination has been reduced significantly due to the development of mycotoxin detection techniques. Numerous effective techniques have been developed since mycotoxins were first discovered in foods and feeds. These include ultra-performance liquid chromatography (UPLC), thin layer chromatography (TLC), quick strip screening tests, enzyme-linked immunosorbent serological assay (ELISA), gas chromatography (GC) combined with flame-ionization detection (FID) and electron-capture detection (ECD), and high-performance liquid chromatography (HPLC) coupled with diode array detection (DAD), ultraviolet light (UV), and fluorescence detection (FLD) (Alshannaq and Yu, 2017; Turner *et al.*, 2015). However, mycotoxin testing is very challenging because of complex sample matrices and low-level mycotoxin contamination.

Recently, there have been a few prospects to improve significantly the performances of detection techniques because of the rapid growth of nanotechnology (Li *et al.*, 2018; Lv *et al.*, 2018; Zhang *et al.*, 2019). According to Zhong (2009), nanomaterials are substances having a length of <100 nm in at least one dimension and created from both inorganic and organic substances. Different nanomaterials have proven to be useful in creating efficient methods for pre-treatment of samples and thus utilized as core of sensing techniques to detect mycotoxins accurately. This has led to significant improvements in detection techniques, including sensitivity, accuracy, and detection time (Goud *et al.*, 2018; Yang *et al.*, 2020a). Various strategies, including chemical, biological, and physical methods, are used effectively for eliminating mycotoxins (Agriopoulou *et al.*, 2020; Luo *et al.*, 2018). Recent advancements in nanomaterials have shown great potential in controlling mycotoxin contamination (Gonzalez-Jartín *et al.*, 2019; Horky *et al.*, 2018). These materials have been found to inhibit production, and absorb and detoxify mycotoxins. Nowadays, advanced nanomaterials are used widely to reduce mycotoxin contamination—a subject of growing interest. However, not many thorough evaluations are available on the application of nanoparticles (NPs) in preventing mycotoxin contamination. Hence, this article provides a comprehensive summary of how emerging nanomaterials are used to control mycotoxin contamination. Various applications include the use of nanomaterials for mycotoxin assay, inhibiting mycotoxin production, adsorbing mycotoxins, and eliminating mycotoxins. The information in this review offers new perspectives on controlling mycotoxins by using innovative nanomaterial-based methods.

Types of Mycotoxins

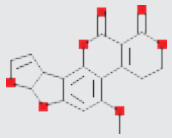
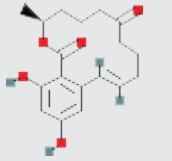
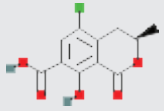
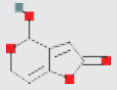
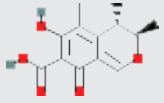
Aflatoxins

Aflatoxins, which are highly toxic mycotoxins, are primarily produced by *Aspergillus spp*., such as parasiticus and flavus. They are considered as the most prevalent mycotoxins (Luo *et al.*, 2018; Xue *et al.*, 2019). It has been reported that there are now more than 20 types of AFT molecules (Table 1). The difurocoumarolactone group is the most significant subgroup, which includes aflatoxin G2 (AFG2) and aflatoxin G1 (AFG1), and the difurocoumarocyclopentenone group, which consists of aflatoxin M1 (AFM1), aflatoxin M2 (AFM2), AFB1, and AFB2 (Ismail *et al.*, 2018). It is inevitable for AFG1, AFG2, AFB1, and AFB2 to be present in both food and feed. Of all these varieties, AFB1, AFB2, AFG1, and AFG2 are found commonly; AFB1 is the most dangerous aflatoxin, followed by AFG1, AFB2, and AFG2. It must be remembered that AFM1 and AFM2, formed from AFB1 and AFB2, respectively, are hydroxylated through metabolites (Esan *et al.*, 2024). It is common to find both AFM1 and AFM2 in some animal products, including dairy products and egg yolks, as well as the flesh of animals that eat feed containing aflatoxins (Kumar *et al.*, 2017). Of all the mycotoxins, AFTs are believed to be most potent. Owing to their interaction with proteins, enzymes, RNA, and DNA, they lead to liver disorders (Da Silva *et al.*, 2023). AFTs are also known for their chronic hepatocarcinogenic, teratogenic, mutagenic, and toxicologic effects (Enyiukwu *et al.*, 2014). According to Luo *et al.* (2018), of all the AFTs, AFB1 is considered as the efficacious and most common carcinogen found in nature. There is a growing body of evidence linking persistent anthrax poisoning to hepatic tumor or malignancy of the liver. Acute cases of aflatoxicosis are reported globally, including India, China, Kenya, and Malaysia. Symptoms include gastrointestinal discomfort, nausea, edema, and in serious circumstances death (Haque *et al.*, 2020; Liew and Mohd-Redzwan, 2018). The AFTs are most commonly found in different nuts, such as peanuts, walnuts, almonds, pistachios, cashews, pecans, and Brazil nuts as well as cereals, such as barley, oats, wheat, rice, and corn. AFTs can also be present in food products made from these items, such as cornflakes, pasta, flour, bread, and breakfast food. Other sources of AFTs include dried fruits, animal products, spices, edible vegetable oils, wines, cottonseed, herbs, animal tissues, milk curd, eggs, and meat (Agriopoulou *et al.*, 2020; Luo *et al.*, 2018). Food items with low AFT levels are easier to find at small-scale farms with limited storage period; however, utilizing bags makes little difference in reducing AFT levels (Fang *et al.*, 2022).

Zearalenone

Zearalenone is primarily developed by different Fusarium species, such as *Fusarium culmorum, F. equiseti, F. graminearum, F. crookwellense*, and *F. semitectum*. This macrocyclic β-resorcyclic acid lactone was first mentioned by Bhatnagar *et al.* (2002) later on Tola and Kebede (2016). The ZEN-producing fungi typically thrive in storage environments having high humidity, excessive moisture, and temperate weather conditions (Luo *et al.*, 2018). ZEN is classified as an estrogenic mycotoxin because of its resemblance to natural estrogens. This leads to a noticeable estrogenic impact on both animals and humans (Alshannaq and Yu, 2017). ZEN's biological decomposition has been studied and is determined to be superior to physical and chemical methods. The biological breakdown of ZEN is effectively carried out by enzymes lactonase, peroxidase, and laccase (Zhang *et al.*, 2023). In particular, females that are exposed to ZEN may have an estrogenic impact that triggers the early onset of puberty (Massart *et al.*, 2008). Additionally, the use of ZEN may result in toxicity because of its ability to stimulate the generation of reactive oxygen species

Table 1. Occurrences, sources, and their effects on various types of mycotoxins.

Mycotoxins	Structure	Fungi source	Occurrences	Health issues	IARC classification	References
Aflatoxins (G1, G2, M1, M2, B1, and B2)		*Aspergillus flavus*, *A. pseudotamarii*, *A. bombycis*, *A. nomius*, *Emericella stellata*, *E. olivicola*, and *E. venezulensis*	Rice, cereals, spices, nuts, and milk	Carcinogenic, mutagenic, immunosuppressive, hepatoxic, and teratogenic	Group 1	Wu and Santella, 2012
Zearalenone (ZEN)		*Fusarium crookwellense, F. equiseti, F. graminearum, F. cerealis, F. incarnatum,* and *F. culmorum*	Soybeans, sorghum, barley, oats, rice, and wheat	Genotoxicity, carcinogenicity, prolapse of vagina, and immunotoxicity	Group 3	Sadrabadi *et al.*, 2016
Ochratoxins (OTA,OTC, and OTB)		*Penicillium verrucosum, Aspergillus auricomus, A. glaucus, Neopetromyces muricatus, A. fonsecaeus, Penicillium carbonarius, Aspergillus niger,* and *P. cyclopium*	Dried vine fruit, wheat, wine, rye, raisins, grape juice, and coffee	Carcinogenic, neurotoxic, protein synthesis inhibition, immunodepressant, and mutagenic	Group 2B	De Girolamo *et al.*, 2020
Patulin (PAT)		*Byssochlamys sp., Pencillium patulum, P. expansum,* and *P. crustosum*	Pears, apricots, peaches, cherries, apples, ans olives	Pulmonary congestion, convulsions, edema, embryo toxicity, dyspnea, and pulmonary edema	Group 3	Omotayo *et al.*, 2019
Fumonisins (FB3, FB1, and FB2)		*Fusarium anthophilum, Alternaria alternate, F. moniliforme, F. napiforme, F. nygamai*, and *F. dlamini*	Milk, corn-based products, asparagus, maize, and rice	Cytotoxicity, immunodepressant immunotoxic, apoptosis, and pulmonary edema	Group 2B	Cortinovis *et al.*, 2013
Trichothecenes (T-2, DON, and HT-2)		*Cephalosporium* sp., *Trichoderma* sp., *Myrothecium* sp., *Stachybotrys* sp., and *Phomopsis* sp.	Cereals	Oral lesions, leukocytosis, anorexia, infertility, diarrhea, and hemorrhage	–	Alshannaq and Yu, 2017
Citrinin (CIT)		*Penicillium expansum, P. citrinum, P. redicicola,* and *P. verrucosum*	Spices, sake, stored grains, red pigments, and cheese	Immunotoxic, hepatotoxic, reproductive toxicity, and embryo toxic	–	Haque *et al.*, 2020
Ergot alkaloids		*Neotyphodium coenophialum, Claviceps fusiformis, C. africanana*, and *C. paspali*	Grass, millet, oats, wheat, and triticale	Gangrenous form, edema of the legs, paraesthesias, neurotoxicity, nausea, blindness, and vomiting	–	Topi *et al.*, 2017

IARC: International Agency of Research on Cancer.

(ROS; El Golli Bennour *et al.*, 2009). Furthermore, ZEN demonstrates stable characteristics if exposed to typical cooking temperatures, although it may be partially removed in high temperature environments (Castelo *et al.*, 1998). ZEN is reported to found in several countries, including Germany, Philippines, China, Japan, Croatia, Iran, Thailand, and Egypt (Agriopoulou *et al.*, 2020; Munkvold, 2017). ZEN is frequently discovered in rye, sorghum, maize, corn, wheat, and barley. Maize stands out among these crops for having a higher ZEN infection rate (Hussein and Brasel, 2001). It is worth mentioning that ZEN contamination of substances takes place concurrently with other pollutants, such as OTA, DON, FB1, and AFB1 (Luo *et al.*, 2018). The majority of studies have included high-dose, short-term exposure in animals, neglecting the subtle chronic effects of low-dose, long-term exposure to toxins, more similar to human exposure (Han *et al.*, 2022).

Ochratoxins

There are three categories of secondary metabolites known as ochratoxins (OTs), namely ochratoxin C (OTC), ochratoxin B (OTB), and ochratoxin A (OTA). Aspergillus and penicillium are the main producers of these metabolites. OTB is a less toxic than OTA because it does not contain chlorine. It is often be found in feeds and foods beside OTA (Udovicki *et al.*, 2018). According to Haque *et al.* (2020), OTC is classified as an ethyl ester form of OTA.

According to Agriopoulou *et al.* (2020) and Alhamoud *et al.* (2019), OTA is the most hazardous and prevalent of the three types of OTs that pollute foods and feeds. It is reported that OTA can damage both liver and kidneys. Additionally, studies have shown that OTA may cause birth defects, neurological damage, cancer, genetic damage, and damage to the immune system (Mantle, 2002; Pitt, 2000). It can obstruct the production of adequate protein by hindering the hepatic and renal systems' hydroxylase to phenylalanine activities because of its similarity to crucial amino acid phenylalanine. It is worth mentioning that OTA can hinder the creation of both RNA and DNA (Alshannaq and Yu, 2017). According to Agriopoulou *et al.* (2020), various food items, such as dried vine fruits, meat species, cereals, milk, alcoholic beverages (e.g. beer and wine), cocoa, coffee, and chocolate, are found to contain OTA. According to Eskola *et al.* (2019), cereals have the highest total exposure to OTA, accounting to approximately 60%.

Aptamers and aptasensors are used to find mycotoxins in food. However, when these sensors are used to detect mycotoxins in a complicated food matrix, their setup has to be optimized. Detoxification employing organic extract, ozone, and cold plasma therapy was also discovered to be a successful treatment. Thus, development of poisonous fungi can be restrained due to biocontrol and detoxication techniques (Ganesan *et al.*, 2022).

Patulin

Patulin (PAT) is a polyketide mycotoxin which is primarily produced by a number of *aspergillus* and penicillium species, including *Penicillium patulum, Aspergillus clavatus, P. griseofulvum, P. crustosum, P. leucopus, P. urticae,* and *P. expansum* (Agriopoulou *et al.*, 2020; Luo *et al.*, 2018). According to Walravens *et al.* (2014), of all the species, P. expansum is known to be the most frequent producer of PAT. So far, studies have shown that PAT can cause various long-term health issues, such as damage to the liver and kidneys, mutagenicity, neurotoxicity, teratogenicity, genotoxicity, and carcinogenesis. In addition, it can also cause immediate health difficulties such as gastrointestinal issues, hemorrhage, nausea, ulceration, and vomiting (Zhong *et al.*, 2018). It has been found that PAT is present in apple-processing products, vegetables, and fruits. It has been also discovered in other fruits, such as grapes, pears, oranges, and their processed variants (Agriopoulou *et al.*, 2020). During production of fruit juices, PAT is transferred without being removed from rotten fruits (Romero Bernal *et al.*, 2019). Furthermore, according to a Chinese law, the European Union (EU), and the US Food and Drug Administration (FDA), the maximum allowed limit of PAT in apple and fruit juices is 50 g/L/kg (Vidal *et al.*, 2019). PAT detoxification in apple-based products requires further research on the fermentation-related PAT degradation process by *Saccharomyces cerevisiae* (brewer's yeast or baker's yeast) and development of debris from the degradation. *S. cerevisiae* CICC 31084 was effective at harmful PAT (Yang *et al.*, 2023).

Fumonisins

Fusarium toxins, also known as fumonisins, are primarily generated by the fungus Fusarium proliferatum and F. verticillioides. According to Rheeder *et al.* (2002), fumonisins are produced under wet and warm environmental conditions. The classic physical and chemical techniques used for removal of mycotoxins have various blockades, such as an unstable effect, significant nutritional loss, influence on the palatability of feed, and difficulties in mass manufacturing. Nevertheless, there are many ways to stop FUMs from getting into the food supply (Qu *et al.*, 2022). In addition, *Aspergillus niger* (*A. niger*) has been shown to create FUMs on grapes and raisins (Mogensen *et al.*, 2010). At present, more than 28 different types of FUMs have been identified and classified into four groups: fumonisin B (FB), fumonisin C (FC),

fumonisin A (FA), and fumonisin P (FP). Among these, FBs (such as FB2, FB3, and FB1) are most prevalent in nature, with FB1 being the most frequently detected FUM with highest concentration, and it is also known to be the primary cancer-causing agent in humans (Alberts *et al.*, 2016; Luo *et al.*, 2018). FUMs are toxic to animals, causing equine horse leukoencephalomalacia as well as pulmonary edema syndrome and hydrothorax and thorax expanding in pigs (Agriopoulou *et al.*, 2020). Additionally, studies have reported a correlation between the consumption of maize kernels contaminated with FUMs and neural tube defects and higher incidences of cancer of the esophagus in humans (Haque *et al.*, 2020).

Trichothecenes

Trichothecenes are produced by many fungus species, such as fusarium, trichoderma, stachybotrys, cephalosporium, verticimonosporium, trichothecium and myrothecium (Udovicki *et al.*, 2018). Presently, more than 200 TCT variants have been identified and are categorized into four groups: A, B, C, and D (Da Silva *et al.*, 2023). Examples of A type variants include HT-2 toxin, neosolaniol (NEO), diacetoxyscirpenol (DAS), and T-2 Toxin. B type variants include DON, fusarenon-X (FX), and nivalenol (NIV), among others. According to Ferrigo *et al.* (2016), A-type TCTs are considered as the most toxic group, compared to type B analogues. As stated by Luo *et al.* (2018) and Haque *et al.* (2020), A-type variants have toxic effects that result in necrotic lesions, myelotoxicity, hematotoxicity, and a slowdown in growth at contact location. These also cause vomiting, hemorrhage, and diarrhea. These toxins are primarily found in cereals, such as maize, rice, barley, rye, oats, and wheat. Similarly, these have been discovered in soybeans, sunflower seeds, peanuts, bananas, potatoes, beer, certain cereal-based noodles, breakfast cereals, and bread (Alshannaq nd Yu, 2017).

Citrinin

Citrinin (CIT) is a secondary benzopyran metabolite that is mostly produced by *Penicillium expansum, Aspergillus spp.,* and *Monascus spp.* CIT is nephrotoxic and genotoxic, affecting both humans and animals. In order to effectively control toxins at various phases of production and processing, adequate Hazard Analysis Critical Control Point (HACCP) plans, good manufacturing practices (GMPs) and good agricultural practices (GAPs) are necessary. Additionally, a number of biological, physical, and chemical techniques are used to reduce CIT formation and contamination and destroy it, thus preventing it from entering the food chain (Kamle *et al.*, 2022). It has been reported that CIT is linked to both pig kidney disease and yellowed rice illness. According to Edite Bezerra da Rocha *et al.* (2014) and Haque *et al.* (2020), CIT and OTA together hindered RNA synthesis in the kidneys of mice. In addition, contact with CIT can have cancer-causing effects, as noted by Luo *et al.* (2018). Stored cereal grains and barley are found to be an excellent setting for growth of the fungus that causes CIT. Additionally, CIT has been discovered in marred beans, dairy products, rice, pomaceous fruits, fruit juices, wheat, nuts, rye, and spices (Haque *et al.*, 2020; Tanaka *et al.*, 2007).

Ergot alkaloids

A lethal alkaloid combination, known as ergot alkaloids, is mostly found in the sclerotias (a compact black or purple mass of hardened fungal mycelium containing food reserves) of Claviceps and Neotyphodium species (Grusie *et al.*, 2018; Haque *et al.*, 2020). According to Grusie *et al.* (2018), the most frequent EAs identified concurrently in contaminated foods are ergocornine, ergocristine, ergocryptine, ergosine, ergometrine, and ergotamine. Accordingly, EA toxicity causes paroxysm, mirage, agalactia, feverishness, and incineration in humans, and hypersensitivity, cramps, decreased productivity, internal hemorrhage, suppression of lactation, miscarriage, diarrhea, and corrosion in livestock (Grusie *et al.*, 2018; Haque *et al.*, 2020; Hulvova *et al.*, 2013). The current investigation discovered that whereas concentrations of EAs found in pelleted grain-based matrices may be higher than in mash feeds of comparable composition, pelleting did not worsen the detrimental physiological effects of ergot. Related heat and pressure of pelleting could make it simpler to extract EAs for tests (Stanford *et al.*, 2022). According to Topi *et al.* (2017), EAs are typically found in various grains, such barley, rye, triticale, oats, wheat, and millets. The highest proportion of fungal contamination among these cereals is observed in rye, as reported by Tittlemier *et al.* (2015).

Nanoparticle-Based Mycotoxin Detection

The utilization of core-shell NPs for mycotoxin detection in particular involves the association of core-shell NPs with aptamers or the use of antibodies for the advancement of biosensors. As shown, different NPs with core shells were created and used in pre-treatment of samples, lateral flow immunoassay (LFIA), chemiluminescence sensors, electrochemical analysis, fluorescence, and surface-enhanced Raman spectroscopy (SERS) detection. This has made possible to detect important mycotoxins, such as AFs, OTA, DON, and ZEN, with extreme sensitivity and selectivity. Notably, every strategy offers benefits of its own. (Zhai *et al.*, 2023).

For accuracy, several analytical methods, such as ELISA, HPLC, and TLC, are available and used frequently for the precise measurement of mycotoxins (Anfossi *et al.*, 2016; Chauhan *et al.*, 2016). Mycotoxins, for instance, are easily distinguished using TLC because of their varying migration velocities over an absorbent material layer (Hussain *et al.*, 2021). By contrast, HPLC separates mycotoxins in mobile phase and measures their amount by means of fluorescence or UV detection (Pandey *et al.*, 2021). The ELISA uses mycotoxin-specific antibodies to detect and quantify mycotoxin levels (Zhan *et al.*, 2021). The present research concentrated on increasing detection limit, time consumption, sample consumption, and convenience of use (Berthiller *et al.*, 2017; Guo *et al.*, 2015; Sadhasivam *et al.*, 2017; Selvaraj *et al.*, 2015). This is because early detection is necessary to safeguard health.

According to practice, NPs are used in two distinct ways in detection systems (Rai *et al.*, 2015; Rhouati *et al.*, 2017). Direct interaction between NPs and identified chemical occurs at the receptor level. This system needs sufficient repeatability and specificity. NPs develop to improve signal to the detector's transducer. Rai *et al.* (2015) have provided an overview of these technologies. The cited study summarized potential methods for immobilizing biomolecules and concluded that mycotoxins involved more investigation into the development of nano biosensors with increased rigidity and toughness. Because of their maximum surface-to-volume ratios, NPs are advantageous in this situation because they can bind larger amounts of mycotoxins (Gontero *et al.*, 2017).

Over the past 10 years, research on nanomaterials had concentrated on metal NPs, polymers, quantum dots (QDs), super paramagnetic NPs, and carbon nanotubes (CNTs). Additionally, the usage of NPs enables diverse surface ornamentation from functional groups, including COOH, CH_3, NH_2, and OH as well as numerous alterations with the help of appropriate ligands. The immune detection of mycotoxins is emphasized in the present research. A fast-evolving method that includes NPs (such as sensitivity) and antibodies (such as specificity) is the lateral flow immuno chromatographic test. The threshold of diagnosis for several mycotoxins is between 0.1 and 10,000 mg/mL using gold NPs of QDs (Xie *et al.*, 2015). For detecting AFL B1, immuno electrodes based on bismuth oxide nanorods were developed (Solanki *et al.*, 2017) (Figure 1). The third-generation immunosensors function by direct electron transfer of analytes to electrodes and has quick response (15 s), hypersensitivity (1.132 A/mg/dL), wide linear spectrum (1–70 mg/dL), and minimal detection threshold (8.715 mg/dL) (Zhang *et al.*, 2004).

Recently, ready-to-use immuno chromatographic test strips with detection threshold of 0.05 and 0.1 mg/mL were suggested for the concurrent identification of T2 toxin and ZEA. Magnetic NPs with an antibody label are used for instant pre-treatment to obtain perfect sensitivity and quick testing (Petrakova *et al.*, 2017). Aptasensors for the simultaneous detection of AFL B1 and OTA A using surface-added Raman scattering are developed using silver(Ag)@gold(Au) core-shell NPs. Plasmonic interaction at the intersection of gold core and Ag shell is the primary source of stable and quantifiable signals in Raman scattering aptasensors (Zhao *et al.*, 2015b).

Multiplex detection in one step of several mycotoxins has been the subject of recent research. This streamlines the whole analysis, regardless of whether it is needed for a device in the form of a strip or another shape (Sun *et al.*, 2016). In order to identify 20 mycotoxins, Kong *et al.* (2016) created semi-quantitative and quantitative multi-immuno chromatographic strips using gold NPs as a marker. The capacity to interpret results with a naked eye is its benefit. According to the estimates made by Kong *et al.* (2016), the sight detection thresholds for FUMs, DONs, AFs, ZEAs, and T2s were different. Sensitivity and reliability are not sufficient for detection. Owing to the fact that plant enzymes alter the structure of mycotoxin derivatives, it is difficult to identify these using standard analytical methods (Berthiller *et al.*, 2013).

As a successful pre-treatment step of masked derivates, enzyme or acid hydrolysis is frequently used prior to mycotoxin testing (Goryacheva and De Saegar, 2012). Mass spectroscopy could also reveal covered up mycotoxins (Aqai *et al.*, 2011; Huybrechts *et al.*, 2015; Nakagawa *et al.*, 2011). Initially, a summary of categorization, the frequency and toxicity traits of prevalent mycotoxins, was provided. Then, after providing description of molecularly imprinted polymer (MIP) composites and an overview of those composites, overly concentrated enhances the functioning of NPs in relation to popular subcategories of sensors based on MIP, including quartz crystal microbalance, electrochemical, chromatography, surface-added Raman scattering, and surface plasmon resonance (SPR) (Mukunzi *et al.*, 2022). NPs might help with mycotoxin separation or detection as well as the emergence of a proof-of-concept tool for locating unidentified updated masked mycotoxins, which is still a significant difficulty. Small peptides are used to extract and clean up mycotoxins in mycotoxin testing, enhancing delicacy with repeatability of conventional monitoring of equipment. Past techniques have a tough time in detecting mycotoxins in food and food products in real time. However, antigen–antibody-based immunoassays can do this. Despite the fact that tiny peptides can be anti-immune complex peptides, competitive antigens, coating antigens, simplifying antibody preparation, or avoiding the use of toxin standards have a crucial role

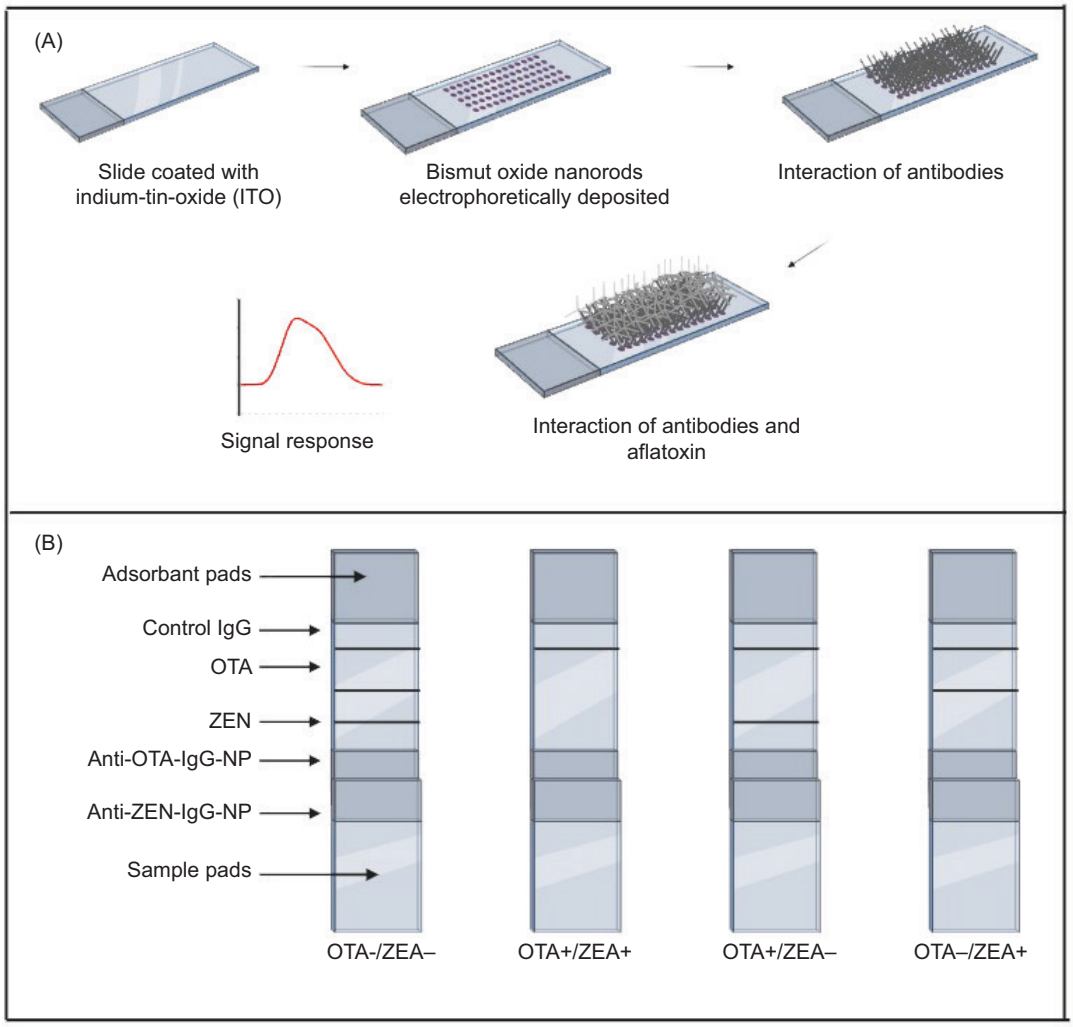


Figure 1. Various immunodetection systems. (A) A signal-amplifying electrosensor that relies on the interaction of antibody along with mycotoxin. (B) A lateral simple immunoassay for the visual identification of mycotoxins.

in mycotoxin detection. Additionally, these strategies have flaws, such as the requirement to employ mycotoxin standards and to consider the complexity and difficulty of creating anti-toxin antibodies (Zhao *et al.*, 2022).

Controlling Mycotoxins with Nanomaterials

Advanced methods for mycotoxin testing

Nanomaterials for tests based on HPLC

For the purification and monitoring of harmful substances in foods, which include aromatic hydrocarbons that are polycyclic (Li *et al.*, 2018), fluoroquinolones mycotoxins (Wen *et al.*, 2020; Yang *et al.*, 2020b) and others nanomaterials, particularly magnetic NPs (MNPs), are used in conjunction using different analyses platforms (e.g. LC-MS/MS and HPLC) (Liu *et al.*, 2020; Zhao *et al.*, 2017b). This study compared the efficacy of ELISA and HPLC-fluorescence techniques for detecting FUM in maize, and found the accuracy of both techniques (as evaluated by trueness and accuracy), with HPLC utilized as a confirmatory method. In our investigation, all performance metrics, including recovery and repeatability data, fulfilled the EU standards for the acceptability of analytical procedures for detection and quantification of FUMs (Sokolovic, 2022). Karami-Osboo *et al.* (2015) used HPLC-UV to analyze DON, with a limit of detection (LOD) of 45 g/kg and a limit of quantitation (LOQ) of 150 g/kg in wheat flour by utilizing Fe_3O_4 MNPs as a cleaning reagent for extraction of mycotoxins. To extract AFB1, AFB2, AFG1, and AFG2 from samples of nuts and cereals, Fe_3O_4 MNPs were also utilized (Karami-Osboo and Mirabolfathi, 2017). These samples were then combined with HPLC equipped with a fluorescence detector to detect AFTs. Notably, Guo *et al.* (2015) used UHPLC-MS/MS in conjunction with magnetic multi-walled carbon nanotubes (m-MWCNTs), magnetic

solid-phase extraction (MSPE), to purify and identify TCTs type A, such as NEO, HT-2 toxin, DAS, and T-2 toxin (Dong *et al.*, 2016) (Figure 2). Used m-MWCNTs as sorbents founded on the same technique for the extraction and detection of ZEN and its derivatives in corns (Han *et al.*, 2017). Additional magnetic NPs are used for HPLC-based mycotoxin testing (Capriotti *et al.*, 2019), including Co_3O_4@C@ MIP (Wu *et al.*, 2018), metal-organic framework (MOF), magnetic nanographene (Durmus *et al.*, 2020; Huang *et al.*, 2019), magnetic zeolitic imidazolate frameworks (ZIFs; Gao *et al.*, 2019), and Fe_3O_4/rGO. Despite the fact that HPLC-based tests have demonstrated excellent empathy, excellent precision, and strong dependability to detect mycotoxins, they are labor-intensive, time-consuming, and difficult, particularly dependent on costly instruments and professional operators (Goud *et al.*, 2019; Zhang *et al.*, 2020).

Nanomaterials-based immunoassays

According to Niu *et al.* (2019) and Xue *et al.* (2019), the basis for immunoassays is the interaction of antibodies with antigens and signal molecules for labeling the contact, and can be recognized from the results of its detection through naked eye and straightforward analytical instruments. Owing to the highly focused detection association of antibody with antigen, immunoassays have been the most widely used detection method for fast analysis in a non-laboratory scenario (Bu *et al.*, 2020; Niu *et al.*, 2019). Owing to its benefits of chemical stability, simple synthesis, and inexpensiveness gold (Au) NPs are frequently employed for mycotoxin detection. In addition, a number of new substances have been researched, showing promise for improving signals. The development of manufactured vibrant NPs for multiplex immunoassay analyte detection (Adunphatcharaphon *et al.*, 2022). Amazingly, the utilization of immunoassays has been benefited greatly from the progress of nanotechnology.

Different nanomaterials, such as covalent organic frameworks (COFs), magnetic particles, silicon NPs, upconversion NPs (UCNPs), QDs, metal nanomaterials, carbon nanomaterials, and MOFs, have drawn growing attention due to their distinctive properties, such as strong fluorescence, variable diameters, improved surface reactivity, and superior electrical 2conductivity. These materials have also been widely used for boosting immunoassay spectacles, particularly sensitivity (Alhamoud *et al.*, 2019; Li *et al.*, 2020; Su *et al.*, 2019). Two novel immunoassay

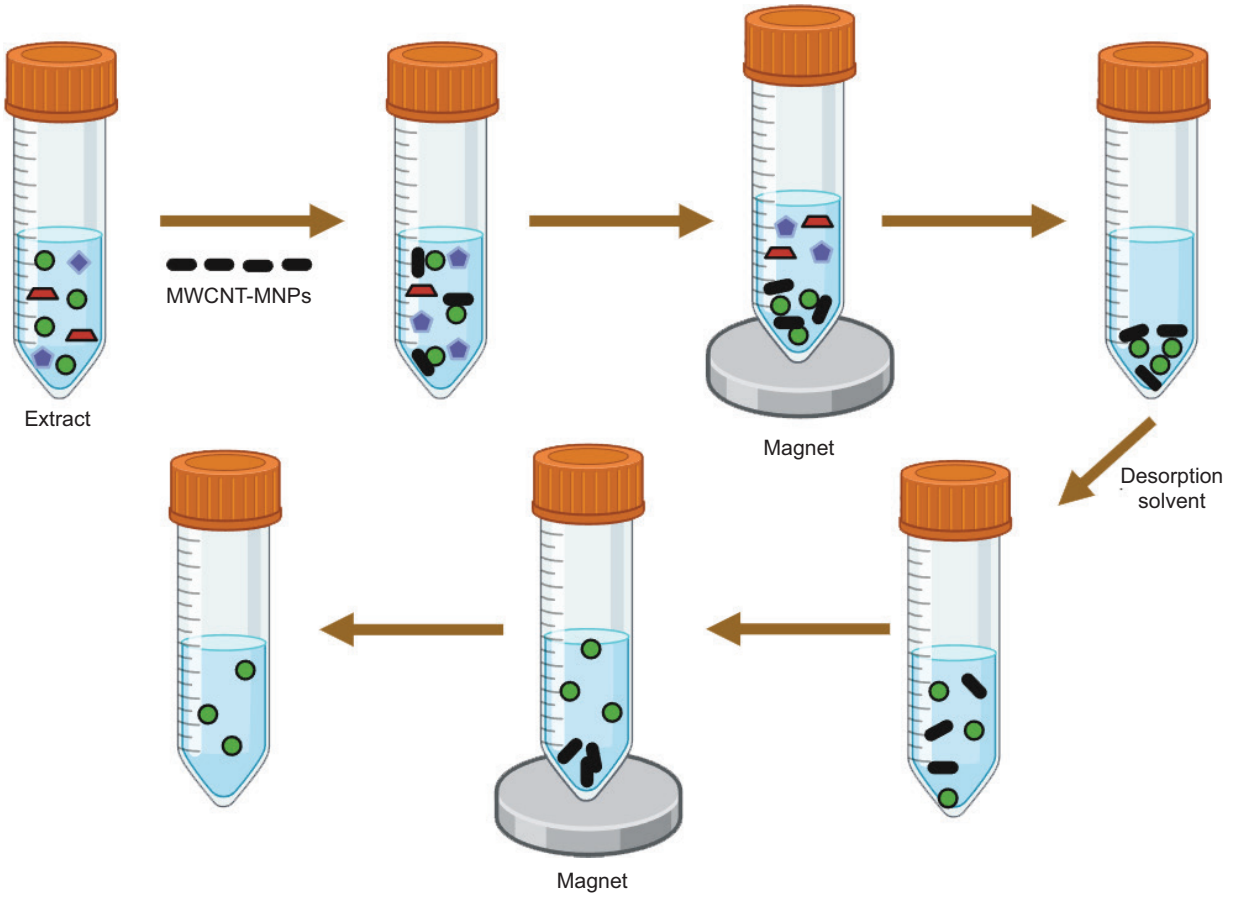


Figure 2. Flowcharts of magnetic solid-phase extraction (MSPE) method.

systems (APN-ELISA and PN-ELISA) for OTA detection were created by using nanobodies as coated antibody and the phage-displayed peptidomimetic and ALP-tagged peptidomimetic fusion as a competing antigen. The operation of recognizing APN-ELISA and PN-ELISA was equivalent to or even superior to mimotope-based immunoassays used for OTA (Yang *et al.*, 2023). Additionally, a wide range of opportunities for nanomaterial-based immunoassays in determining the presence of mycotoxins have been realized (Chen *et al.*, 2020; Liu *et al.*, 2020; Rai *et al.*, 2015; Wang *et al.*, 2016; Xue *et al.*, 2019). Nanomaterials have played a crucial role in these nanomaterials-based immunoassays, which immobilize biomolecules and alter electron transport by lowering or increasing of its producing signals (Xue *et al.*, 2019). The noticeable enhancing of signal in immunoassays is caused by the utilization of nanomaterials having a surface that is naturally nanoscale-sized and can provide conducive biocompatible environment for the immobilization of biomolecules. Some NPs, such MNPs, MOFs, AgNPs, COFs, and Au NPs, have wide surfaces and strong biocompatibility, which make them useful for binding biomolecules such as cysteamine, antibodies, and enzymes as well as acting as electroactive indicator carriers (Sharma *et al.*, 2010; Xue *et al.*, 2019). As an illustration, MOFs, AgNPs, MNPs, and Au NPs have been utilized to immobilize enzymes, and synthetic materials of NPs and enzymes investigate act as signal indicates for immunoassays signal amplification (Goud *et al.*, 2018; Xue *et al.*, 2019). Au NPs, QDs, and UCNPs are the examples of nanomaterials with exceptional optical properties that could be used for signaling mycotoxin immunoassay categorization (Jiang *et al.*, 2020; Xue *et al.*, 2019). Particularly, silver/gold (Ag/Au) NPs are worthy of enhancing information in mycotoxin immunoassays (Xue *et al.*, 2019). Recently, a novel SERS-based subsequent-generation immunosensor targeting and additionally determining six mycotoxins (T-2 toxin, ZEN, FB1, OTA, DON, and AFB1) in maize employed Raman reporter molecules (4-mercaptobenzoic acid [MBA] and 5,5-dithiobis-2-nitrobenzoic acid [DTNB]) to modify Au@Ag core-shell NPs for SERS nanoprobes.

T-2 toxin, ZEN, FB1, DON, OTA, and AFB1 could be recognized using the recommended SERS-based flowing laterally immunosensor with LODs = 8.6, 0.96, 0.11, 0.26, 15.7, and 6.2 mg/mL, respectively (Zhang *et al.*, 2020; Figure 3). In order to keep enhancing the degree of specificity in the immunoassays of mycotoxins, emerging nanomaterials with enzyme-like catalytic activity (specifically nanozyme) can be further investigated as catalytic labels that substitute enzymes for signal generation/amplification of immunoassays in future investigations (Niu *et al.*, 2019; Zhang *et al.*, 2019, 2020). Furthermore, despite the fact that the use of nanomaterials-based immunoassays for mycotoxin detection is common, the superior antibodies utilized in these procedures still have certain inherent limitations, such as expensiveness, complicated preparation, and time-consuming. As a possible substitute for antibodies, several molecular recognition components, such as aptamers and MIPs, have been created as biosensors for identification of mycotoxins.

Nanomaterials-based aptasensors

Aptamers are a subset of molecular recognition elements having unique reactions with a variety of analytes.

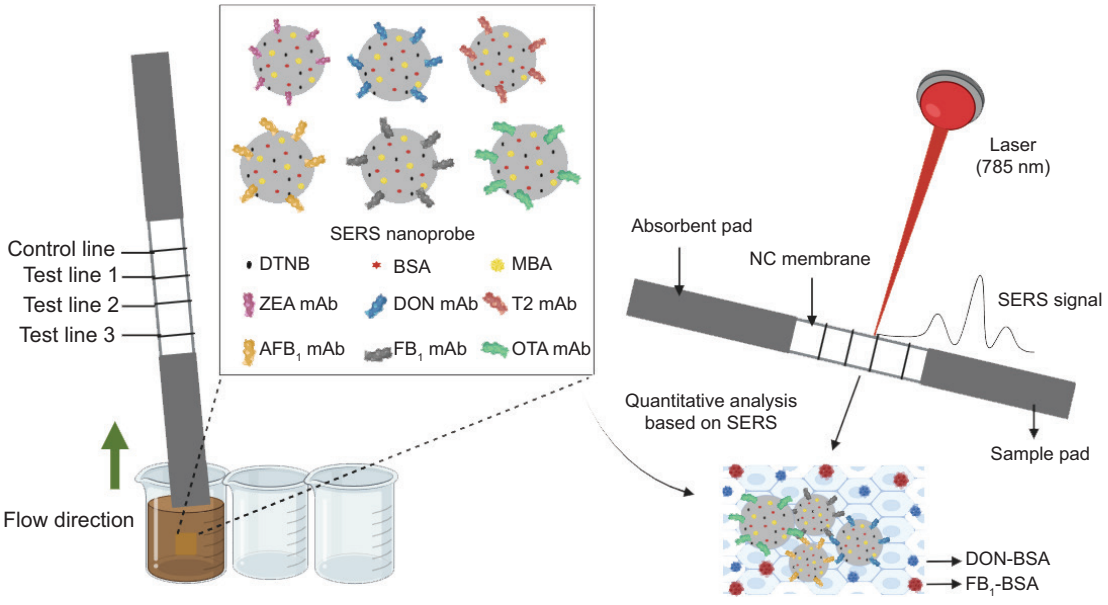


Figure 3. Representation of a multiplex SERS-based lateral circulation of immunosensor for mycotoxin analysis.

These are formed from molecules of peptides or nucleic acid. Aptamers are widely used in the creation of aptasensors because to their recognition selectivity toward numerous analytes (Goud *et al.*, 2018; Sharma *et al.*, 2015). Different nanomaterials, such as carbon-based nanomaterials, magnetic NPs, metal oxide NPs, UC NPs, COFs, MOFs, and noble metal NPs (such as graphene and CNTs), fit together into aptasensors to produce new aptasensors based on nanomaterials (Sharma *et al.*, 2015; Xue *et al.*, 2019). Furthermore, the detection of mycotoxins has been extensively caused by these aptasensors based on nanomaterials (Goud *et al.*, 2019; Luo *et al.*, 2020; Zhu *et al.*, 2020).

Nanomaterials play a few key roles, such as alternative to enzyme labels (Bulbul *et al.*, 2015; Tian *et al.*, 2020) fluorescence quencher, immobilization support signal creation, signal amplification, etc., in aptasensors based on nanomaterials for mycotoxin screening (Goud *et al.*, 2018; Sun *et al.*, 2018). Developing nanozymes in the construction of aptasensors for mycotoxin assay (Goud *et al.*, 2019; Rhouati *et al.*, 2017) has outlined the application of smart sensors that utilize nanomaterials in mycotoxin testing. Advanced nanozymes have been employed effectively in the aptasensing of mycotoxins as signal generation/amplification labels (Chatterjee *et al.*, 2020; Tian *et al.*, 2019). Aptasensor with colorimetry for identifying ZEN was constructed by employing ZEN aptamer and Au NPs with peroxidase-mimicking activity (Lin *et al.*, 2024). Although clustered regularly interspaced short palindromic repeats and CRISPR-associated protein 9 (CRISPR/CAS 9) technology has been implemented in a number of aptasensor scaffolds and has significantly increased their efficacy, there are still some significant technological issues that need to be resolved. Breakthroughs may potentially result by putting together cutting-edge computational modeling and algorithms, anti-matrix interference materials, user-friendly portable diagnostic equipment, the Cas-aptamer-based sensor which can detect a wide range of biological processes (Suliman Maashi, 2023). ZEN could be linearly detected with the suggested aptasensor of 10–250 mg/mL with a 10-mg/mL LOD as reported by Sun *et al.* (2018). Similar to this, a new colorimetric aptasensor was built on aptamer-controlled $MnCo_2O_4$ nanozyme activity for OTA testing. A low LOD of 0.08 mg/mL allowed for the selective detection of OTA in maize samples using the existing aptasensor (Huang *et al.*, 2018).

Recently, a new colorimetric aptamer biosensor was created to detect simultaneously OTA and AFB1 in agricultural products. Thymolphthalein (TP)-GO and Fe_3O_4/GO were combined, utilizing AFB1 aptamer, to provide a platform to carry out AFB1 testing. The platform separation took place with AFB1 present. Owing to the production of TP when alkaline conditions are present, the solution took a dark blue hue following the magnetic separation of Fe_3O_4/GO. Similar to this, another platform was created by combining Fe_3O_4@Au and Au NPs using complimentary OTA aptamer strands. Owing to the presence of OTA, platforms made of Fe_3O_4@Au crumbled, allowing Fe_3O_4@Au to separate magnetically. When the base material 3,3′,5,5′-tetramethylbenzidine (TMB) is catalyzed by Au NPs exhibiting enzyme-like activity, a distinct color change takes place. AFB1 was exponentially detected between 5 mg/mL and 250 mg/mL using designed aptamer biosensors, while OTA was identified linearly between 0.5 mg/mL and 80 mg/mL (Zhu *et al.*, 2020). Despite nanomaterial-based aptasensors having already been used widely in mycotoxin testing, their commercial success is significantly hindered by intricate designs and expensive amplification processes of aptamer. Likewise, for the recognition of small molecules, nanomaterial-based aptasensors require a lot of energy and produce nonspecific interactions, which limit to some extent the scope of their application.

Mycotoxin sensors based on nanomaterials

Molecularly imprinted polymer, an exceptional biomimetic substance, is commonly employed as a recognition component for biosensors with regard to the antibody–antigen understanding concept in conjunction with antibodies and aptamers (Alhamoud *et al.*, 2019; Cieplak and Kutner, 2016). The MIPs have emerged as an effective substitute for antibodies for producing sensors and have achieved major advancements in the application of mycotoxin testing because of benefits, such as potential applications, high specificity, quick binding kinetics, easy preparation, good stability, and low cost in harsh environments (Alhamoud *et al.*, 2019; Pacheco *et al.*, 2015).

Based on its manner of detection or immobilized biorecognition element, biosensors can be categorized as follows. First, a biosensor's transducer type-optical, electrochemical, thermal, or mass-based-can determine its detecting method with respect to the biorecognition element technique, mycotoxin sensing methods concentrate on immunosensors or aptasensors, which use antibodies or aptamers as biorecognition elements. The used MIPs are novel synthetic biorecognition elements. A particular analyte must be recognized and associated by a biorecognition element, regardless of the molecular structure of a bioreceptor. Analyte contact (and potential binding) and the biological recognition event (transduction) combine to produce a proportionate signal that is amplified and transformed via a transducer to calculate analyte concentration (Meira *et al.*, 2023).

The capacity of NPs for signal production and amplification is successfully linked with particular recognition features of MIPs to further enhance the features of mycotoxin detectors based on MIPs (Xue *et al.*, 2019).

MIP's deficiency in conductivity and electrocatalytic activity makes it difficult to be used in practical applications. Because improved affinity and binding kinetics are made possible, conventional MIPs make task simpler when attached to a transducer surface. A potent tool for their usage in the field of sensing has been developed by the manufacture of nano-sized MIPs for mycotoxins analysis, either solely or in conjunction with NPs. As a result, scientists are urged to use both new and NPs at hand to expand the applications of MIP composite materials. The two main factors that contribute to this are the predominance of serological testing in diagnosis and the technical difficulties that traditional molecular imprinting must overcome (Mukunzi *et al.*, 2022). Numerous nanomaterials, such as MOFs, QDs, CNTs, and metal NPs, have been used in developing MIP-based sensors for detecting mycotoxins (Bagheri *et al.*, 2018; Goud *et al.*, 2018). A novel electrochemical sensor to identify OTA was created by modifying multi-walled CNTs with glassy carbon electrode and MIP. OTA could be detected directly in the range of 0.050–1.0 M using the existing glassy carbon electrode (GCE)/MIP/MWCNT with an LOD of 0.0041 M and an LOQ of 0.014 M by Pacheco *et al.* (2015). Another work used chitosan (CS) composites with Ru(bpy)32^{+}-doped silica NPs (Ru@SiO_2 NPs), Au NPs, and MIP-modified GCE to effectively construct a novel MIP-based electrochemical luminescence (MIP-ECL) sensor for the ultrasensitive identification of FB1. Ru@SiO_2 NPs were used as ECL luminophores in the suggested ECL sensor, while Au NPs functioned as intensifying ECL with a localized surface plasmon resonance (LSPR) source. According to Zhang *et al.* (2017a), the developed MIP-ECL sensor allowed for the identification of FB1 with a wide range of 0.001–100 mg/mL with an LOD of 0.35 mg/mL. In particular, revolutionary AgNPs@ZnMOF nanozymes' exceptional peroxidase-mimicking catalytic activity and MIP's exclusive recognition ability, Bag herietal were integrated succeeded in developing a new, highly effective nanozymes-based MIP fluorescence sensor to identify PAT, which ranged from 0.1 to 10 mol/L with a minimal LOD of 0.06 mol/L (Bagheri *et al.*, 2018). Contrary to a popular belief regarding MIPs that there is a potential recognition component for sensor development, they lack the inherent bioreceptors like antibodies aqueous environment selectivity (Ashley *et al.*, 2017; Figure 4).

Nano Approaches to Reduce the Danger of Mycotoxin

Nanomaterials with antifungal properties that prevent mycotoxin

Antibacterial NPs have been developed for the past 10 years as a remedy for harmful bacteria's drug resistance.

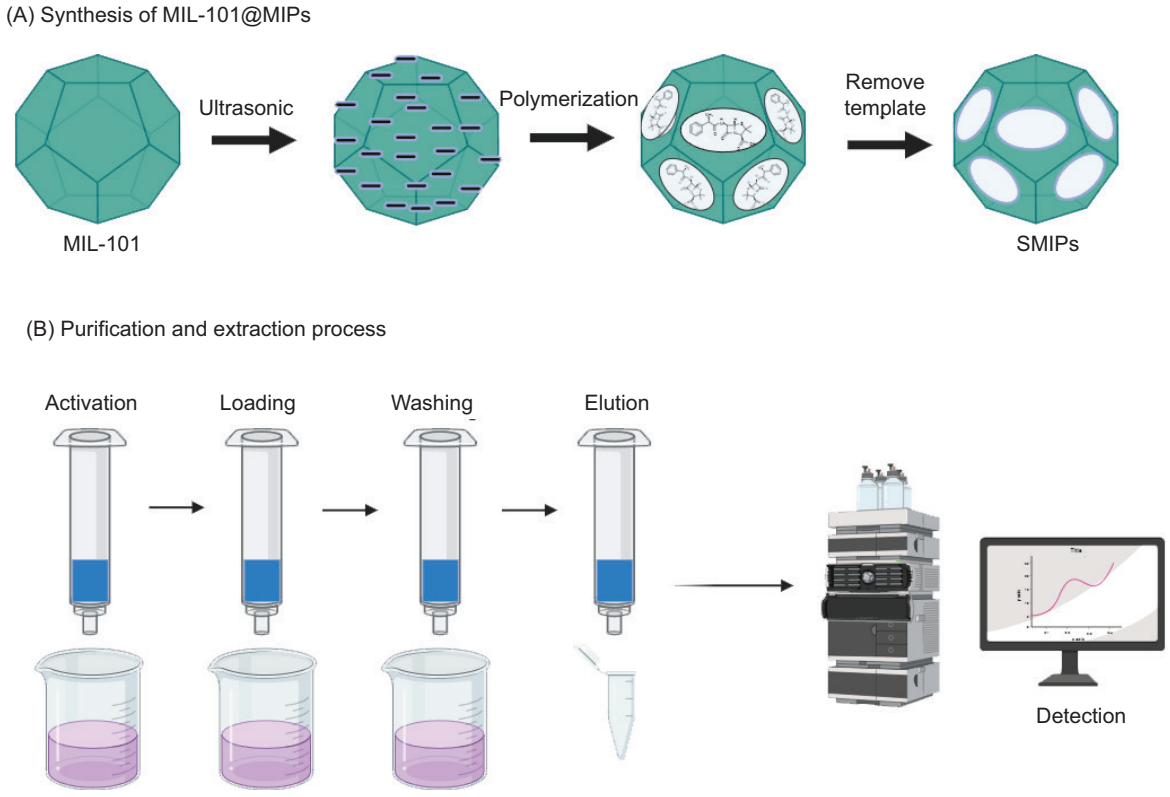


Figure 4. The method of (A) MIL-101@MIPs synthesis; (B) extraction and purification (Huang *et al.*, 2019).

Their capacity to combat the production of mycotoxin has been hampered by the distinctions between bacteria and fungus. Bacteria have only one cell, but the majority of fungus has several cells. Additionally, bacteria have three different forms whereas fungi have a variety of shapes that can result in the production of mycelium. Owing to all these variations, fungi are more resilient and antibiotic-resistant (Sureka *et al.*, 2014). It is now feasible to utilize antifungal medications that are very effective, thanks to the development of antifungal nanomaterials and introduction of nanotechnology. The generation of mycotoxin is now inhibited by the use of several nanomaterials (Hassanzadeh Davarani *et al.*, 2018; Roque *et al.*, 2017). Antifungal NPs, which are simple to make on a big scale, could be used in practice to avoid the occurrence of mycotoxins. Recent scientific studies, summarized in Table 2, claim that the antifungal approach is divided into two different paths. In general, there are two types of nanomaterial-based antifungal strategies: those that encapsulate antifungal compounds into polymeric nanomaterials and release them when the right conditions (such as the presence of enzymes, higher temperature, and pH variation) are available, and those that directly depend on nanomaterials to prevent the growth of fungi. First, a polymeric nanocage is used to enclose an antifungal substance whereas cargo release from nanopolymers is possible at right conditions (enzymes existence, pH shift, or a higher temperature); the instability in air is perhaps the method's biggest drawback. Second, the impact of inhibition is only achieved by NPs. This technique primarily utilizes stable, quick-acting, and environment-friendly metal NPs. The creation of nanobiocomposites from plants, microbials, and animal sources that exhibit reduced toxicity and enhance their primary properties is another benefit of green synthesis (Adelere and lateef, 2016). Various nanogels have been used, as described previously (Beyki *et al.*, 2014; Khalili *et al.*, 2015), to encapsulate antifungal drugs against fungus. Enhancement in antifungal activity is achieved by encapsulating Thyme essential oil and Mentha piperita essential oil in nanogel chitosan–benzoic acid and nanogel chitosan–cinnamic acid, respectively (Beyki *et al.*, 2014; Khalili *et al.*, 2015). Additionally, because of their exceptional antibacterial abilities and metal NPs with a high surface area–volume ratio, these NPs have been regarded as one of the best antifungal agents (Abd-Elsalam *et al.*, 2017). Other NPs that have been reported to be effective against fungi include magnesium oxide (MgO) NPs, zinc oxide (ZnO) NPs, nitrogen-doped titanium oxide–palladium oxide (TiO_N/PdO) NPs, and N- and F-co-doped TiO_2 NPs as stated by Abd-Elsalam *et al.* (2017) (Figure 5). As reported by Abd-Elsalam *et al.* (2017), preventing mycotoxin-producing fungi from expanding is possible by ZnO NPs.

The biosynthesized Ag NPs show exceptional capabilities for suppressing four mycotoxigenic fungus strains, such as *A. ochraceus, Fusarium solani* (*F. solani), A. flavus,* and *A. alternata*. Notably, Zhao *et al.* (2017b) evaluated the results of Ag NPs on the suppression of AFT formation and Luo *et al.* (2020) appropriately synthesized Ag NPs for

Table 2. Synthesized nanoparticles used for antifungal activity.

Type of nanoparticles	Fungal species	Dose concentration	Zone size	References
Silver	*Alternaria flavus*	5 µg/mL	4.5 nm	Zhao *et al.*, 2017a
Alumina nanoparticle, Ag-doped titan oxide	*Fusarium oxysporium*	400 mg/L	200 nm	Shenashen *et al.*, 2017
Chitosan silver nanocomposites	*Fusarium oxysporum*	100 µg/mL	370 nm	Dananjaya *et al.*, 2017
Copper	*Penicillium digitatum*	20 and 60 µg/mL	NA	Khamis *et al.*, 2017
Sliver	*Candida parapsilosis*	0.01 mmol/mL and 0.02 mmol/mL	22 mm and 27 mm	Hawar *et al.*, 2022
Selenium	*Fusarium mangifera*	300 µg/mL	14 mm	Shahbaz *et al.*, 2023
Iron oxide	*Pencillium chrysogenum*	0.5 mg/mL	28.67 ± 1.53 mm	Praveen *et al.*, 2018
Silver	*Phaseolina*	1,000 µg/mL	13 mm	Vijayabharathi *et al.*, 2018
Iron oxide	*Cladosporium herbarum*	75 µg/mL	40 mm	Henam *et al.*, 2019
Selenium	*Solani*	1 mM	45 mm	Hashem *et al.*, 2021
MgO and FeO	*Alternaria alternata*	0.5 mg/mL	16.33 ± 1.15 mm and 15.66 ± 0.57 mm	Koka *et al.*, 2019
ZnO and Fe-doped ZnO	***N**iger*	40 µL	13 mm and 18 mm	Ferin Fathima *et al.*, 2020
Silver	*Alternaria* sp.	100 µL	21.6 ± 1.5 mm	Win *et al.*, 2020
Silver	*Rhizopus stolonifer*	0.1, 0.2, and 0.5 mg/mL	90 mm	Moreno-vargas *et al.*, 2023
ZnO–CuO	*Fusarium oxysporum*	1,000 µg/mL	22.8 ± 0.76 mm	Gaber *et al.*, 2023

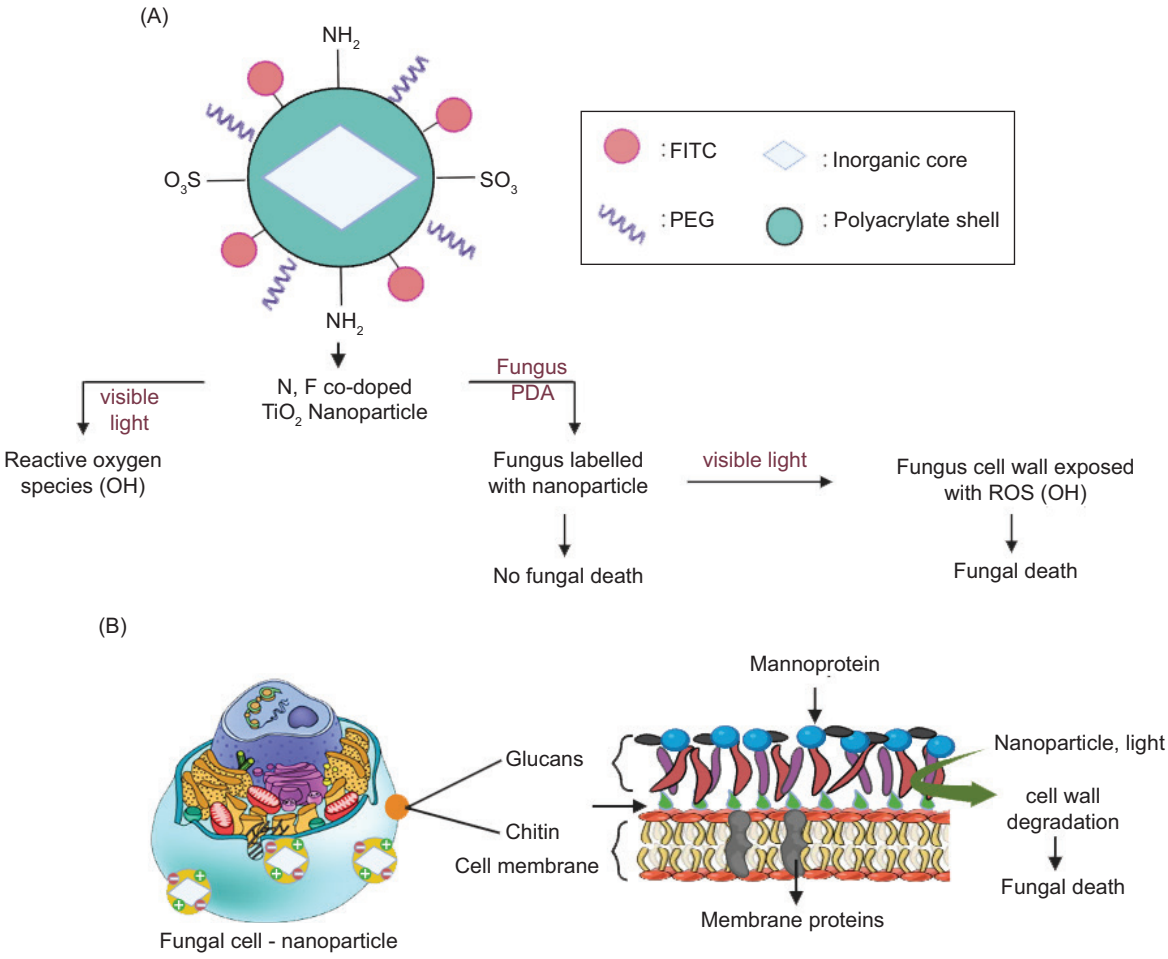


Figure 5. (A) Experimenting with N- and F-co-doped TiO_2 NPs' antifungal activity and chemical structure. (B) Suggested mechanism of N- and F-co-doped TiO_2 NPs' antifungal activity. Under visible light irradiation, the labeled NP produces hydroxyl radicals (OH) at the surface of fungal cell wall. The fungal cell wall's glucan and chitin layers react with this radical, degrading the cell wall and causing cell death.

the suppression of A. flavus growth with a common width of 4.5 nm. Fusarium oxysporum fungus development in vegetables, such as tomatoes, and fruits could be entirely stopped by visible light irradiation (Mukherjee *et al.*, 2020). The treatment of Fusarium head blight (FHB) could be benefited from the combination of Ag NPs and DON-reducing fungicides, which may also be employed to create fungicidal formulations. Therefore, future research is required to assess Ag NPs' antibacterial properties in a realistic agricultural setting (Jian *et al.*, 2022). Ag NPs interfere with intracellular structures, alter transcription throughout the genome, and disrupt the integrity of fungal cell wall and cell membrane to impede their development. However, Ag NPs inhibit the UvKmt6-mediated H3K27me3 alteration, which suggests that Ag NPs and mycotoxin-reducing fungicides could be used in tandem to reduce rice false smut disease. These findings aid in understanding Ag NPs' usage and potential drawbacks in the governance of plant fungal infection (Wen *et al.*, 2023).

The maximum zone of inhibition against *Penicillium chrysogenum (P. chrysogenum*) with iron oxide (FeO) NPs was 28.67 ± 1.53 mm at 0.5 mg/mL (Praveen *et al.*, 2018). The green-synthesized Ag NPs have a considerable antifungal impact on the plant pathogen *Candida parapsilosis* at a concentration of 0.01–0.02 mmol/mL with the maximium zone of inhibition being 22–27 mm (Hawar *et al.*, 2022). The highest level of antifungal activity was demonstrated by selenium (Se) NPs at a concentration of 300 µg/mL and an inhibitory zone of 14 mm (Shahbaz *et al.*, 2023). According to Vijayabharathi *et al.* (2018), synthesized Ag NPs inhibited *Macrophomina phaseolina (M. phaseolina*) with a high zone of inhibition of 13 mm at 1,000 µg/mL. With a concentration of 75 µg/mL and a size range of 40 mm, Fe_2O_3 NPs appear to have more antifungal action against Cladosporium herbarum (Henam *et al.*, 2019). In contrast, 1 mM of Se NPs produced an inhibitory zone of 45 mm and exhibited the greatest antifungal action against Rhizoctonia solani (R. solani)

(Hashem *et al.*, 2021). In contrast to other fungal species, green MgO and FeO NPs demonstrated antifungal activity toward the fungus disease Alternaria alternata. Both MgO and FeO NPs exhibit greatest inhibitory efficacy at a concentration of 0.5 mg/mL, compared to other concentrations. The largest size range is 15.66–0.57 mm and 16.33 × 1.15 mm (Koka *et al.*, 2019). ZnO- and Fe-doped ZnO NPs suppressed A. niger's antifungal activity with a high zone of inhibition of 13–18 mm at 40 µL (Ferin Fathima *et al.*, 2020). At a concentration of 100 µL in the zone range of 21.6 ± 1.5 mm, *Alternaria sp.* showed the highest antifungal activity in green production of Ag NPs (Win *et al.*, 2020).

Two fungus species, Rhizopus stolonifer and F. solani, were used in the manufacture of Ag NPs to study the antifungal activity as a function of time and concentration. According to Moreno-Vargas *et al.* (2023), the greatest zone was strongest in the 120 h of testigo, at 0.1, 0.2, and 0.5 mg/mL, which demonstrated a 90-mm zone of inhibition. When compared to other produced NPs, zinc oxide–copper oxide (ZnO–CuO) NPs had the strongest antifungal activity, but the starting materials (zinc. AQnacetate, copper acetate, and cross flow filtration) had no effect. Additionally, ZnO–CuO NPs demonstrated good antifungal efficacy against F. oxysporum, with an inhibition zone of 22.8 ± 0.76 mm at a dose of 1,000 µg/mL (Gaber *et al.*, 2023). Interestingly, photocatalytic and antifungal activity and disinfection mechanism of PdO NPs against F. graminearum macroconidia was investigated in visible light. The PdO NPs were able to adsorb significantly on the outer layer of F. graminearum macroconidium due to opposing surface charges of macroconidium and PdO NPs, thus facilitating the photocatalytic disinfection of macroconidia. The antifungal effect of PdO NPs on F. graminearum macroconidia could be due to the ability of ROS to destroy cell walls and membranes (Zhang *et al.*, 2013) (Figure 6).

Nanoparticles for mycotoxin adsorption

Emerging nanomaterials have shown tremendous potential because of their extensive surface area (Ramadan *et al.*, 2020; Santana-Mayor *et al.*, 2020). Mycotoxins have diverse structural compositions, which result in a range of physical and chemical characteristics. Although mycotoxins may often be classified as either nonpolar or polar molecules, certain mycotoxins are reportedly intermediate in nature. TCT is a polar mycotoxin whereas ZEN is nonpolar, and both FUMs and AFTs are reportedly very polar (Horky *et al.*, 2018; Stroka and Maragos, 2016). Nanomaterials respond to a variety of mycotoxins because of former's polar and nonpolar behavior and adjust their characteristics to a variety of physicochemical conditions.

Numerous NPs, such as magnetic Fe_3O_4 modifiers, chitosan polymeric NPs, and carbon nanomaterials, are used extensively in mycotoxin adsorption (Horky *et al.*, 2018; Ramadan *et al.*, 2020). According to Horky *et al.* (2018), because of colloidal stability in different pH values, large surface area per weight, inherent inertness, superior adsorptive capability, and high stability, carbon nanomaterials (e.g. CNTs, nanodiamonds, and magnetic graphene) are currently used extensively to adsorb mycotoxins. The chemical structures that enable surface functionalization and provide a binding affinity to various mycotoxins are present in nanodiamonds, such as hydroxylation, carboxylation, and hydrogenation (Shoala, 2020). Horky *et al.* (2018) calculated the absorption capabilities of nanodiamonds for OTA and AFB1, which were

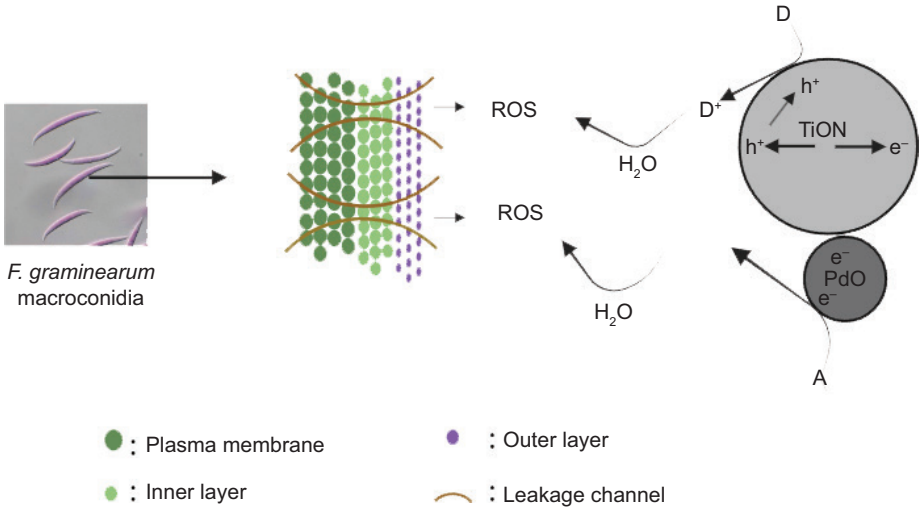


Figure 6. Palladium-modified nitrogen-doped titanium oxide (TiO_N/PdO) photocatalyst's antifungal efficacy and mechanism against agricultural pathogenic F. graminearum (Zhang *et al.*, 2013).

approximately 10 g/mg and 5 g/mg, respectively. The CNTs with single or many walls are also used extensively in the process of adsorption of mycotoxins, such as AFTs, TCTs, and ZEN because of their adsorption capabilities (Horky *et al.*, 2018; Shoala, 2020). There are reports of several mycotoxins being adsorbed by chitosan NPs simultaneously. For AFB1, OTA, FUM1, and ZEN, glutaraldehyde-crosslinked chitosan demonstrated exceedingly encouraging adsorption capability. However, DON and T-2 are not clearly adsorbed by glutaraldehyde-crosslinked chitosan (30%) (Zhao *et al.*, 2015b). According to Luo *et al.* (2017), a nontoxic chitosan-coated Fe_3O_4 NP was effectively created with juice-pH for incorporating PAT-simulated environment. The chitosan-coated Fe_3O_4 NP demonstrated efficient adsorption for PAT with an optimum capacity of 6.67 mg/g for adsorption, and featured excellent adsorption characteristics such as low toxicity and good magnetic properties (Luo *et al.*, 2017). Furthermore, a study created MIP-coated magnetic NPs (MIP-MNPs) for identification, quick adsorption, outstanding absorbing capacity, and excellent selectivity of OTA (Turan and ¸Sahin, 2016). In order to remove PAT from apple juice, Sun *et al.* (2020) created a new and powerful adsorbent with a magnetic molecular imprint (i.e. Fe_3O_4@SiO_2@CS-GO@MIP). Additionally, Fe_3O_4@SiO_2@CSGO@MIP demonstrated that PAT had a maximum adsorption capacity of 7.11 mg/g and could be removed within 24 h, removing more than 90% of the substance (Sun *et al.*, 2022).

A study revealed that synthetic mesoporous silica nanoparticles (MSNs) with a larger Brunauer, Emmett and Teller (BET) technique surface area and a variety of morphologies, measuring 39.97 × 7.85 nm, adsorb up to 70% of AFB1 in aqueous environment within 15 min. MSNs exhibit great blood biocompatibility (with no hemolytic activity) and have no effect on the survival of 3-day transfer inoculum 3 × 105 (NIH3T3) cells *in vitro*. We further verified that AFB1-induced cytotoxicity in NIH3T3 cells *in vitro* was reduced by MSNs. Silanol groups and small size, porosity, and large surface area of mesopores could be responsible for MSN's effective AFB1 adsorption. The polarity and size of AFB1, in addition to its physical and chemical characteristics, had a role in how well it bounds to MSNs (Savi *et al.*, 2023).

Nanomaterial for removal of mycotoxins

Mycotoxin detoxification is seen as a never-ending process in the food sector. The removal of mycotoxins has been the subject of numerous strategies, including the chemical ones (such as ammonization, chemical agents, and ozonation), physical ones (such as irradiation, thermal processes, adsorption, cold plasma, UV, sorting, and microwave heating), and biological ones (such as microorganism and enzymes) (Figure 7) (Pankaj *et al.*, 2018; Sun *et al.*, 2019). However, the methods used to remove mycotoxins from the body have significant drawbacks.

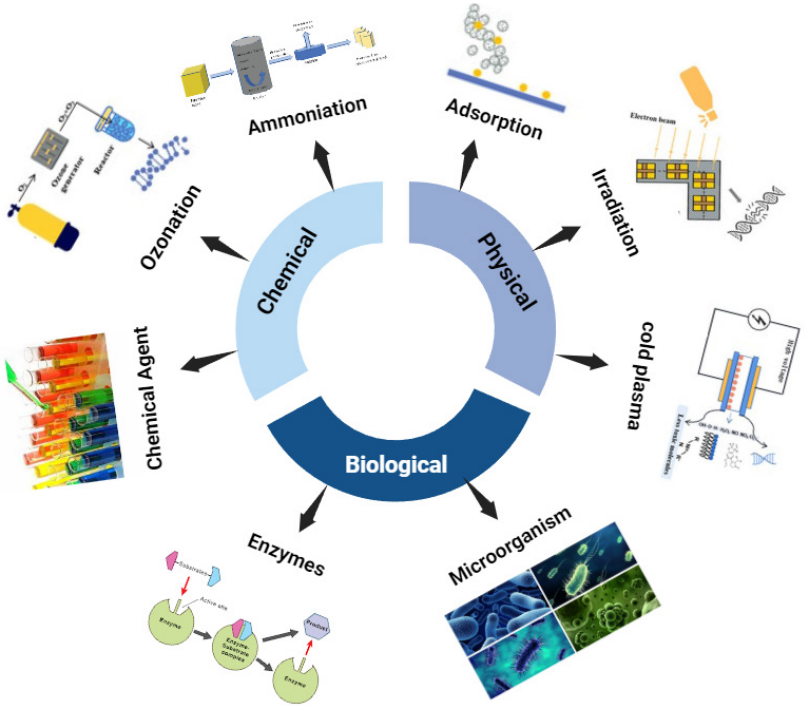


Figure 7. Removal of mycotoxins by nanomaterials using physical, chemical, and biological techniques.

For instance, chemical techniques can result in residual issues, mycotoxin adsorption might result in secondary contamination, and biological approaches might be constrained by demanding environmental conditions, a protracted growing time, and expensive costs (Sun *et al.*, 2019).

Chemical techniques

Ammonization: Under very alkaline conditions, the amide bond of OTA undergoes hydrolysis to form non-toxic OTα and phenylalanine. This process is reversible. During the initial phases of investigation, ammonization emerged as a prevailing approach for detoxifying OTA. This approach exhibits detoxifying properties on different crops polluted with OTA, such as corn and wheat, without resulting in the generation and buildup of harmful breakdown byproducts (Ding *et al.*, 2023). Ammoniating wheat at high pressure (60 psi) and normal temperature lowers the concentration of mycotoxins by 79% (Samuel *et al.*, 2021). Similarly, treating contaminated cocoa shells with a 2% potassium carbonate solution at 90°C for 10 min could reduce 83% of OTA (Samuel *et al.*, 2021).

Ozonation: Ozone is generated from the atmosphere or from a gas mixture containing oxygen and an energy source, such as corona discharge, UV light, or electrolysis. The corona discharge technology is extensively employed in several industries. This process involves the passage of oxygen or air across gaps between two electrodes (ground and dielectric) that are separated by energetic dielectric materials. During this process, oxygen is separated into oxygen atoms, which then mix with oxygen molecules to produce ozone (Pandiselvam *et al.*, 2017). Ozone has a potential to impact the integrity and permeability of cell membranes, resulting in the leaking of cell contents. In addition, it interacts with proteins, such as DNA and RNA, and interferes with the structure of nucleic acids, resulting in the demise of cells. (An *et al.*, 2024) Alternatively, ozone can chemically break down C8-C9 double bond by acting as an electrophile, resulting in the formation of primary ozonides. These ozonides can then degrade into smaller ozonated compounds, including aldehydes, ketones, and organic acids.

Physical techniques

Irradiation: OTA was eliminated by irradiating infected corn with γ-rays. It demonstrated that extremely reactive radicals of γ-rays could damage OTA molecules' ability to form double bonds with aromatic rings. Dosage of radiation is a crucial determinant impacting the process (Ding *et al.*, 2023). The research conducted by Khalil *et al.* (2021) investigated the impact of γ-rays on the removal efficiency of OTA in both dry form and various aqueous solutions. The findings revealed that OTA in aqueous solutions was readily degraded by γ-rays whereas OTA in dry form exhibited lower susceptibility to degradation. These results suggest that γ-rays may not be an optimal approach for degrading OTA in grains.

Adsorption: Adsorption is a significant method for eliminating OTA by physical means. The process involves combining adsorption material with OTA to form a molecule that prevents the mycotoxin from being absorbed in the body through the gastrointestinal system. This combination is then removed by excretion (Quintela *et al.*, 2013). The utility model offers the benefits of cost-effectiveness, a straightforward approach, and great efficiency. Physical adsorption is a surface process that occurs due to attractive forces prevalent between molecules, such as van der Waals forces and electrostatic interactions. In the case of OTA, these forces are between the negative charge of OTA and the positive charge of adsorbent. The phenolic hydroxyl groups of molecules engage in interactions with hydrophobic materials. The adsorption effect is influenced by several parameters, such as pore size, surface charge quantity, charge distribution, and specific surface area of adsorbent (Ding *et al.*, 2023).

Cold plasma: Cold plasma is a phase of matter that exists beside solid, liquid, and gaseous phases. Cold plasma has the ability to efficiently break down and decrease the development of mycotoxins in both food and feed (Loi *et al.*, 2023). Cold plasma technology operates by producing reactive chemicals, such as O_2, O_3, OH, NO, and NO_2, which dismantle the structure of OTA and alleviate oxidative stress. This process leads to alteration or breakdown of OTA (Mohammadi *et al.*, 2021). Cold plasma offers the benefit of rapid and effective degradation of OTA. However, its application is rather restricted due to the requirement of specialized equipment, resulting in its occasional use for degradation of toxins (An *et al.*, 2024).

Biological techniques

Microorganisms: Distinct processes by which microorganisms might lessen mycotoxin contamination include biotransformation (Piotrowska, 2021) and adsorption to cell walls, as discussed in Section 5.2 'Atoxigenic Aspergillus strains'. Various genera of filamentous fungi (such as Pleurotus, Armillariella, Armoracia, Trametes, Rhizopus, Trichoderma, Clonostachys, Cladosporium, and Aspergillus), yeasts (such as Saccharomyces, Pichia, Candida, Kluyveromyces, Yarrowia, Rhodotorula, and Rhodosporidium), and bacteria (such as Bacillus, Metschnikowia, Komagataella, Streptomyces, Rhodococcus, Pseudomonas, Pediococcus, Lactiplantibacillus, Enterobacter, Cupriavidus, and Brevibacterium) are capable of performing the biotransformation of AFs (Nahle *et al.*, 2022).

Enzymes: Traditionally, enzymatic degradation is considered as specific. However, this is not the case for these

particular enzymes. Their ability to break down AFs is dependent on their strong oxidative capacity, which is not limited to AFs alone as substrates. Laccases and peroxidases can synergistically interact with redox mediators, thereby expanding the range of substrates that these enzymes can act upon (Loi *et al.*, 2023). When examined in protein and carbohydrate-rich diets, these enzymes have been demonstrated found to facilitate the creation of crosslinks and significantly alter the nutritional, technical, and rheological characteristics of foods. Modifications of some foods have been shown to enhance their nutritional and technical features (Loi *et al.*, 2020). Therefore, it is important to conduct a meticulous examination for each specific situation to utilize these enzymes successfully.

The advantages of as a technique for progressive oxidation, photocatalytic degradation recently demonstrated significant potential for mycotoxin detoxification as a result of their low cost, environmental friendliness, ease of minimal pressure and temperature fluctuations, absence of secondary pollutants, and operation (Bai *et al.*, 2017; Jamil *et al.*, 2017). Amazingly, cutting-edge nanomaterials have become a popular research topic in mycotoxin detoxification sector and have played a significant role in the photocatalytic destruction of mycotoxins (Wu *et al.*, 2020; Zhou *et al.*, 2020). In order to prevent food contamination, a detailed examination of the mechanisms of detoxification and their capacity to preserve nutritional and organoleptic qualities, as well as toxicity assessments of the leftover components, is necessary (Hamad *et al.*, 2022). While photocatalytic technology is mostly used to degrade AFB1 and DON in the aqueous phase, usage of photocatalysts on food infected by fungi is still in its early stage. The application of photocatalytic technology for detoxification of mycotoxins will be expanded if new or more photocatalysts are found to destroy efficiently other species of mycotoxins. Future research will pay close attention to the routes and toxicities of the byproducts of mycotoxin destruction in food samples by photocatalysts as well as changes in food quality and nutrition. Finally, widespread usage of photocatalytic technology can successfully remove mycotoxin contamination from agro-foods (Jing *et al.*, 2023).

To date, numerous nanomaterials, such as titanium dioxide (TiO_2), UCNP@TiO_2, graphene/ZnO hybrids, g-C_3N_4, WO_3/RGO/g-C_3N_4, and Fe_2O_3, are used in the photocatalytic destruction of mycotoxins, (Bai *et al.*, 2017; Zhou *et al.*, 2020). According to Sun *et al.* (2019), a straightforward hydrothermal technique was used to create an AFB1 photocatalytic degradation using an activated carbon and TiO_2-based catalyst (AC/TiO_2). Owing to the enhanced visible light intensity and higher surface area of AC/TiO_2 composites, when exposed to UV-Vis light, 98% of degrading efficiency of material toward AFB1 could be achieved., which was greater than the degradation efficiency of bare TiO_2 (76%) (Sun *et al.*, 2019). Surprisingly, Wang *et al.* (2018) created a new photocatalyst (NaYF4:Yb,Tm@TiO_2 composite; UCNP@TiO_2) for the near-infrared (NIR) light-induced photocatalytic breakdown of DON (Zhou *et al.*, 2020). Their team recently used UCNP@TiO_2 to photocatalyze the degradation of DON under UV-Vis light and was able to identify three DON products because of deterioration (Wu *et al.*, 2020). Additionally, TiO_2 NPs were used to accelerate PAT breakdown in apple juice exposed to UV light. PAT in apple juice could be broken down to a limit of <10 mg/L using TiO_2 NPs in 180 min (Douanla, 2019).

Development Propensity and Key Challenges

A number of cutting-edge mycotoxin analysis and control technologies depend on nanomaterials, which have been the subject of ongoing research and development throughout the last decade. Although much of ground is covered, still several major problems need fixing:

1. More innovative nanomaterials with new characteristics and multifunctionality should be found. Multifunctional composite nanomaterials could be created by mixing NPs with diverse properties. These NPs may enable more colorful detection and control tactics and perhaps entity integration. Nanomaterials could be used for detection, removal, and detoxification, reducing time and money, boosting detection effectiveness, and monitoring the detoxification process.

2. Safety and use of nanomaterials must be assessed. Nanomaterials have been employed widely in antifungal, mycotoxin absorption, and degradation; however, mycotoxin pollution control is a new phenomenon. Unknown health effects of nanomaterials could limit their usage for the sake of food safety. Nanomaterials used for mycotoxin control may be transferred to food by contact, which is their main drawback. Nanomaterial safety and applicability must be evaluated using applicable models or methods before their generalization and commercialization.

3. Nanomaterials, functional nucleic acids, biomimetic materials, and gene editing (CRISPR-Cas, clustered regularly interspaced short palindromic repeats and associated proteins) technology are needed to advance molecular biotechnology. These identification components greatly accelerate sensitive and selective detecting technologies. Because aptamers against AFB1 and OTA are well developed, several sensors are created using the same. Organic

nanotechnology and biorecognition molecules help identify mycotoxins for control.

4. Computing technology integrates NPs to a greater extent. Most of the nanomaterial-based mycotoxin detection methods are still confined to laboratories because they require bulky and expensive apparatus to capture optical and electrochemical signals; this limits the manufacture of miniaturized commercial devices. More work must be done to combine nanomaterials with intelligent and information technology with automated spectrum processing and chemometric algorithms, such as portable and user-friendly Raman spectrometers.

Conclusions and Prospective

Numerous articles are written on detection and control of mycotoxin contamination based on nanomaterials, which has become a prominent area of research in recent years. These techniques excel in three key areas: sensitivity, efficiency, and practicability. To ensure food safety, this study compiled the latest findings on the use of nanomaterials to build various measurements and control techniques to control mycotoxins, including methods to limit fungal development and absorption and degradation of mycotoxins. Specifically, distinct characteristics, intended usage, and suitability of each nanomaterial for each detection or control method are detailed and examined extensively. With the ongoing development and research in the field of nanomaterials, it is expected that this contribute more to ensuring the safety of food processing and production, as well as human health, by helping to create sophisticated and creative methods for detecting and controlling mycotoxins and other factors that pose a threat to human wellness. Researchers in the fields of nanotechnology and food science are expected to work together in the future to utilize multifunctional nanomaterials that inhibit the growth of mycotoxins discovered in food and feed.

Author Contributions

Author contributions for this research article are as follows. Lavanya Ganesan: methodology, data curation, writing original draft, and investigation; Balasubramanian Balamuralikrishnan: conceptualization, writing original draft, selected bibliographic sources, visualization, and writing-review and editing; Sri Kalpana: formal analysis and selected bibliographic sources; Viji Maluventhen: formal analysis, editing, and selected bibliographic sources; Arumugam Maruthupandian: conceptualization and writing review and editing. All the authors revised and approved the final manuscript.

Data Availability Statement

The data sets utilized and/or analyzed in this work are available on reasonable request.

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Conflicts of Interest

The authors stated that they had no conflict of interest to declare. The authors had no known competing financial interests or personal relationships that had influenced this paper.

References

Abdallah, M.F., Gado, M., Abdel sadek, D., Zahran, F., El-Salhey, N.N., Mehrez, et al., 2024. Mycotoxin contamination in the Arab world: highlighting the main knowledge gaps and the current legislation. Mycotoxin Research 40(1*):* 19–44. https://doi.org/10.1007/s12550-023-00513-2

Abdel-Hadi, A. M., Awad, M. F., Abo-Dahab, N. F., & ElKady, M. F. (2014). Extracellular synthesis of silver nanoparticles by Aspergillus terreus: biosynthesis, characterization and biological activity. Biosci. Biotechnol. Res. Asia, 11(3), 1179–1186. https://doi.org/10.13005/bbra/1503

Abdel-Hafez, S. I., Nafady, N. A., Abdel-Rahim, I. R., Shaltout, A. M., Daròs, J. A., & Mohamed, M. A. (2016). Assessment of protein silver nanoparticles toxicity against pathogenic Alternaria solani. 3 Biotech, 6, 1–12. https://doi.org/10.1007/s13205-016-0515-6

Abd-Elsalam, K.A., Hashim, A.F., Alghuthaymi, M.A. and Said-Galiev, E., 2017. Nanobiotechnological strategies for toxigenic fungi and mycotoxin control. In: Food preservation. Alexandru Mihai Grumezescu (Ed.), Elsevier, Amsterdam, the Netherlands, pp. 337–364. https://doi.org/10.1016/B978-0-12-804303-5.00010-9

Adelere, I.A. and Lateef, A., 2016. A novel approach to the green synthesis of metallic nanoparticles: the use of agro-wastes, enzymes, and pigments. Nanotechnology Reviews 5*:* 567–587. https://doi.org/10.1515/ntrev-2016-0024

Adunphatcharaphon, S., Elliott, C.T., Sooksimuang, T., Charlermroj, R., Petchkongkaew, A. and Karoonuthaisiri, N., 2022. The evolution of multiplex detection of

mycotoxins using immunoassay platform technologies. Journal of Hazardous Materials 432: 128706. https://doi.org/10.1016/j.jhazmat.2022.128706

Agriopoulou, S., Stamatelopoulou, E. and Varzakas, T., 2020. Advances in occurrence, importance, and mycotoxin control strategies: prevention and detoxification in foods. Foods 9(2): 137. https://doi.org/10.3390/foods9020137

Alberts, J.F., van Zyl, W.H. and Gelderblom, W.C.A., 2016. Biologically based methods for control of fumonisin-producing fusarium species and reduction of the fumonisins. Frontiers in Microbiology 7(548): 548. https://doi.org/10.3389/fmicb.2016.00548

Alhamoud, Y., Yang, D., Fiati Kenston, S.S., Liu, G., Liu, L., Zhou, H., et al., 2019. Advances in biosensors for the detection of ochratoxin A: bioreceptors, nanomaterials, and their applications. Biosensors and Bioelectronics 141: 111418. https://doi.org/10.1016/j.bios.2019.111418

Alshannaq, A. and Yu, J.-H., 2017. Occurrence, toxicity, and analysis of major mycotoxins in food. International Journal of Environmental Research and Public Health 14(6): 632. https://doi.org/10.3390/ijerph14060632

An, N.N., Shang, N., Zhao, X., Tie, X.Y., Guo, W.B., Li, D., et al., 2024. Occurrence, regulation, and emerging detoxification techniques of aflatoxins in maize: a review. Food Reviews International 40(1): 92–114. https://doi.org/10.1080/87559129.2022.2158339

Anfossi, L., Giovannoli, C. and Baggiani, C., 2016. Mycotoxin detection. Current Opinion in Biotechnology 37: 120–126. https://doi.org/10.1016/j.copbio.2015.11.005

Aqai, P., Peters, J., Gerssen, A., Haasnoot, W. and Nielen, M.W.F., 2011. Immunomagnetic microbeads for screening with flow cytometry and identification with nano-liquid chromatography mass spectrometry of ochratoxins in wheat and cereal. Analytical and Bioanalytical Chemistry 400: 3085–3096. https://doi.org/10.1007/s00216-011-4974-7

Ashley, J., Shahbazi, M.-A., Kant, K., Chidambara, V. A., Wolff, A., Bang, D. D. and Sun, Y., 2017. Molecular lyim printed polymers for sample preparation and biosensing in food analysis: progress and perspectives. Biosensors and Bioelectronics 91: 606–615. https://doi.org/10.1016/j.bios.2017.01.018

Aslam, N., Rodrigues, I., McGill, D.M., Warriach, H.M., Cowling, A., Haque, A. and Wynn, P.C., 2016. Transfer of aflatoxins from naturally contaminated feed to milk of Nili-Ravi buffaloes fed a mycotoxin binder. Animal Production Science 56: 1637–1642. https://doi.org/10.1071/AN14909

Babaei, E., Dehnad, A., Hajizadeh, N., Valizadeh, H., & Reihani, S. F. S. (2016). A study on Inhibitory Effects of Titanium Dioxide Nanoparticles and its Photocatalytic Type on Staphylococcus aureus, Escherichia coli and Aspergillus flavus. Applied Food Biotechnology, 3(2), 115–123. https://doi.org/10.22037/afb.v3i2.10571

Bagheri, N., Khataee, A., Habibi, B. and Hassanzadeh, J., 2018. Mimetic Ag nanoparticle/Zn-based MOF nanocomposite (AgNPs@ZnMOF) capped with molecularly imprinted polymer for the selective detection of patulin. Talanta 179: 710–718. https://doi.org/10.1016/j.talanta.2017.12.009

Bai, X., Sun, C., Liu, D., Luo, X., Li, D., Wang, J., et al., 2017. Photocatalytic degradation of deoxynivalenol using graphene/ZnO hybrids in aqueous suspension. Applied Catalysis B: Environmental 204: 11–20. https://doi.org/10.1016/j.apcatb.2016.11.010

Bennett, J., 1987. Mycotoxins, mycotoxicoses, mycotoxicology and mycopathologia. Springer, Cham, Switzerland. https://doi.org/10.1007/BF00769561

Ben Taheur, F., Kouidhi, B., Al Qurashi, Y.M.A., Ben Salah-Abbes, J. and Chaieb, K., 2019. Review: biotechnology of mycotoxins detoxification using microorganisms and enzymes. Toxicon 160: 12–22. https://doi.org/10.1016/j.toxicon.2019.02.001

Berthiller, F., Brera, C., Iha, M.H., Krska, R., Lattanzio, V.M.T., MacDonald, S., et al., 2017. Developments in mycotoxin analysis: an update for 2015–2016. World Mycotoxin J. 10: 5–29. https://doi.org/10.3920/WMJ2016.2138

Berthiller, F., Crews, C., Dallasta, C., De Saeger, S., Haesaert, G., Karlovsky, P., et al., 2013. Masked mycotoxins: a review. Molecular Nutrition & Food Research 57: 165–18. https://doi.org/10.1002/mnfr.201100764

Berthiller, F., Maragos, C.M. and Dallasta, C., 2016. Introduction to masked mycotoxins. In: Dallasta, C. and Berthiller, F. (eds.) Masked mycotoxins in food: formation, occurrence and toxicological relevance, vol. 24. Royal Society of Chemistry, London, pp. 1–13. https://doi.org/10.1039/9781782622574-00001

Beyki, M., Zhaveh, S., Khalili, S. T., Rahmani-Cherati, T., Abollahi, A., Bayat, M., et al., 2014. Encapsulation of Mentha piperita essential oils in chitosan-cinnamic acid nanogel with enhanced antimicrobial activity against Aspergillus flavus. Industrial Crops and Products 54: 310–319. https://doi.org/10.1016/j.indcrop.2014.01.033

Bhatnagar, D., Yu, J. and Ehrlich, K.C., 2002. Toxins of filamentous fungi. Chemical Immunology 81: 167–206. https://doi.org/10.1159/000058867

Brown, K.A., Mays, T., Romoser, A., Marroquin-Cardona, A., Mitchell, N.J., Elmore, S.E. and Phillips, T.D., 2014. Modified hydra bioassay to evaluate the toxicity of multiple mycotoxins and predict the detoxification efficacy of a clay-based sorbent. Journal of Applied Toxicology 34: 40–48. https://doi.org/10.1002/jat.2824

Bu, T., Yao, X., Huang, L., Dou, L., Zhao, B., Yang, B., et al., 2020. Dual recognition strategy and magnetic enrichment based lateral flow assay toward Salmonella enteritidis detection. Talanta 206: 120204. https://doi.org/10.1016/j.talanta.2019.120204

Bulbul, G., Hayat, A. and Andreescu, S., 2015. A generic amplification strategy for electrochemical aptasensors using a non-enzymatic nanoceria tag. Nanoscale 7(31): 13230–13238. https://doi.org/10.1039/C5NR02628H

Capriotti, A.L., Cavaliere, C., La Barbera, G., Montone, C.M., Piovesana, S. and Lagana A., 2019. Recent applications of magnetic solid-phase extraction for sample preparation. Chromatographia 82: 1251–1274. https://doi.org/10.1007/s10337-019-03721-0

Castelo, M.M., Sumner, S.S. and Bullerman, L.B., 1998. Stability of fumonisins in thermally processed corn products. Journal of Food Protection 61(8): 1030–1033. https://doi.org/10.4315/0362-028X-61.8.1030

Chatterjee, B., Das, S.J., Anand, A. and Sharma, T.K., 2020. Nanozymes and aptamer-based biosensing. Materials Science for Energy Technologies, 3: 127–135. https://doi.org/10.1016/j.mset.2019.08.007

Chauhan, R., Singh, J., Sachdev, T., Basu, T. and Malhotra, B. 2016. Recent advances in mycotoxins detection. Biosensors and Bioelectronics 81: 532–545. https://doi.org/10.1016/j.bios.2016.03.004

Cheat, S. and Oswald, I.P., 2016. Kolf-clauw, M. mycotoxin outbreak in animal feed. CRC Press-Taylor & Francis, Boca Raton, FL, pp. 257–286.

Chen, C., Yu, X., Han, D., Ai, J., Ke, Y., Wang, Z. and Meng, G. 2020. Non-CTAB synthesized gold nanorods-based immunochromatographic assay for dual color and on-site detection of aflatoxins and zearalenones in maize. Food Control 118: 107418. https://doi.org/10.1016/j.foodcont.2020.107418

Cieplak, M. and Kutner, W., 2016. Artificial biosensors: how can molecular imprinting mimic biorecognition? Trends in Biotechnology 34(11): 922–941. https://doi.org/10.1016/j.tibtech.2016.05.011

Cortinovis, C., Pizzo, F., Spicer, L.J. and Caloni, F., 2013. Fusarium mycotoxins: effects on reproductive function in domestic animals—a review. Theriogenology 80: 557–564. https://doi.org/10.1016/j.theriogenology.2013.06.018

Cunha, S.C., Sa, S.V.M. and Fernandes, J.O., 2018. Multiple mycotoxin analysis in nut products: occurrence and risk characterization. Food and Chemical Toxicology 114: 260–269. https://doi.org/10.1016/j.fct.2018.02.039

Dallasta, C., Berthiller, F., Adam, G., Maragos, C., Suman, M., Jestoi, M., et al., 2015. Masked mycotoxins in food: Formation, occurrence and toxicological relevance. Royal Society of Chemistry, London.

Dal Pozzo, M., Viegas, J., Kozloski, G.V., Stefanello, C.M., da Silveira, A.M., Bayer, C. and Santurio, J.M., 2016. The effect of mycotoxins adsorbents beta glucans or montmorillonite on bovine ruminal fermentation in vitro. Acta Scientiae Veterinariae. 44: 6. https://doi.org/10.22456/1679-9216.80851

Dananjaya, S.H.S., Erandani, W., Kim, C.H., Nikapitiya, C., Lee, J. and De Zoysa, M., 2017. Comparative study on antifungal activities of chitosan nanoparticles and chitosan silver nano composites against Fusarium oxysporum species complex. International Journal of Biological Macromolecules 105: 478–488. https://doi.org/10.1016/j.ijbiomac.2017.07.056

Da Silva, J.L., Oreste, E.Q., Dias, D. and Garda-Buffon, J., 2023. Electrochemistry applied to mycotoxin determination in food and beverages. Food Analytical Methods 16(3): 541–566. https://doi.org/10.1007/s12161-022-02434-9

De Girolamo, A., Ciasca, B., Pascale, M. and Lattanzio, V.M., 2020. Determination of zearalenone and trichothecenes, including deoxynivalenol and its acetylated derivatives, nivalenol, T-2 and HT-2 toxins in wheat and wheat products by LC-MS/MS: a collaborative study. Toxins 12: 786. https://doi.org/10.3390/toxins12120786

Dellafiora, L., Dall'Asta, C., & Galaverna, G. (2018). Toxicodynamics of mycotoxins in the framework of food risk assessment—an in silico perspective. Toxins, 10(2), 52. https://doi.org/10.3390/toxins10020052

Dellorto, V., Baldi, G. and Cheli, F., 2015. Mycotoxins in silage: checkpoints for effective management and control. World Mycotoxin Journal 8: 603–617. https://doi.org/10.3920/WMJ2014.1866

Ding, L., Han, M., Wang, X. and Guo, Y. 2023. Ochratoxin A: overview of prevention, removal, and detoxification methods. Toxins 15(9): 565. https://doi.org/10.3390/toxins15090565

Dong, M., Si, W., Wang, W., Bai, B., Nie, D., Song, W., et al., 2016. Determination of type A trichothecenes in coix seed by magnetic solid-phase extraction based on magnetic multi-walled carbon nanotubes coupled with ultra-high performance liquid chromatography-tandem mass spectrometry. Analytical and Bioanalytical Chemistry 408(24): 6823–6831. https://doi.org/10.1007/s00216-016-9809-0

Douanla, M.M.N., 2019. Photocatalytic disinfection of patulin using titania in apple juice. Cape Peninsula University of Technology, Cape Town, South Africa.

Durmus, Z., Zengin Kurt, B., Gazioglu, I., Sevgi, E. and Kizilarslan Hancer, C., 2020. Spectrofluorimetric determination of aflatoxin B1 in winter herbal teas via magnetic solid phase extraction method by using metal-organic framework (MOF) hybrid structures anchored with magnetic nanoparticles. Applied Organometallic Chemistry 34(3): e5375. https://doi.org/10.1002/aoc.5375

Edite Bezerra da Rocha, M., Freire, F.D.C.O., Erlan Feitosa Maia, F., Izabel Florindo Guedes, M. and Rondina, D., 2014. Mycotoxins and their effects on human and animal health. Food Control 36(1): 159–165. https://doi.org/10.1016/j.foodcont.2013.08.021

Edwards, S.G., 2004. Influence of agricultural practices on fusarium infection of cereals and subsequent contamination of grain by trichothecene mycotoxins. Toxicology Letters 153: 29–35. https://doi.org/10.1016/j.toxlet.2004.04.022

El Golli Bennour, E., Bouaziz, C., Ladjimi, M., Renaud, F. and Bacha, H., 2009. Comparative mechanisms of zearalenone and ochratoxin A toxicities on cultured HepG2 cells: is oxidative stress a common process? Environmental Toxicology: An International Journal 24(6): 538–548. https://doi.org/10.1002/tox.20449

Enyiukwu, D., Awurum, A. and Nwaneri, J., 2014. Mycotoxins in stored agricultural products: implications to food safety and health and prospects of plant-derived pesticides as novel approach to their management. Greener Journal of Microbiology and Antimicrobials 2(3): 32–48. https://doi.org/10.15580/GJMA.2014.3.0521014241

Esan, O.O., Okanlawon, A.A., Ogunro, B.N., Abiola, J.O., Olaogun, S.C. and Aliyu, V.A. 2024. Seasonal variation of mycotoxin levels in poultry feeds and feed ingredients in Oyo State, Nigeria. Mycotoxin Research 40(2): 319–325. https://doi.org/10.1007/s12550-024-00530-9

Eskola, M., Kos, G., Elliott, C.T., Hajslova, J., Mayar, S. and Krska, R., 2019. Worldwide contamination of food-crops with mycotoxins: validity of the widely cited 'FAO estimate' of 25%. Critical Reviews in Food Science and Nutrition 60(16): 2773–2789. https://doi.org/10.1080/10408398.2019.1658570

Fang, L., Zhao, B., Zhang, R., Wu, P., Zhao, D., Chen, J., et al., 2022. Occurrence and exposure assessment of aflatoxins in Zhejiang province, China. Environmental Toxicology and Pharmacology 92: 103847. https://doi.org/10.1016/j.etap.2022.103847

Ferin Fathima, A., Jothi Mani, R., Sakthipandi, K., Manimala, K. and Hossain, A., 2020. Enhanced antifungal activity of pure and iron-doped ZnO nanoparticles prepared in the absence of reducing agents. Journal of Inorganic and Organometallic Polymers and Materials, 30: 2397–2405. https://doi.org/10.1007/s10904-019-01400-z

Ferrigo, D., Raiola, A. and Causin, R., 2016. Fusarium toxins in cereals: occurrence, legislation, factors promoting the appearance and their management. Molecules 21(5): 627. https://doi.org/10.3390/molecules21050627

Freire, L. and Santana, A.S., 2018. Modified mycotoxins: an updated review on their formation, detection, occurrence, and toxic effects. Food and Chemical Toxicology 111: 189–205. https://doi.org/10.1016/j.fct.2017.11.021

Gaber, S.E., Hashem, A.H., El-Sayyad, G.S. and Attia, M.S., 2023. Antifungal activity of myco-synthesized bimetallic ZnO-CuO nanoparticles against fungal plant pathogen Fusarium oxysporum. Biomass Conversion and Biorefinery 14(15): 1–15. https://doi.org/10.1007/s13399-023-04550-w

Ganesan, A.R., Mohan, K., Rajan, D.K., Pillay, A.A., Palanisami, T., Sathishkumar, P. and Conterno, L., 2022. Distribution, toxicity, interactive effects, and detection of ochratoxin and deoxynivalenol in food: a review. Food Chemistry 378: 131978. https://doi.org/10.1016/j.foodchem.2021.131978

Gao, S., Wu, Y., Xie, S., Shao, Z., Bao, X., Yan, Y., et al., 2019. Determination of aflatoxins in milk sample with ionic liquid modified magnetic zeoliticimidazolate frameworks. Journal of Chromatography B 1128: 121778. https://doi.org/10.1016/j.jchromb.2019.121778

Ghasemian, E., Naghoni, A., Tabaraie, B., & Tabaraie, T. (2012). *In vitro* susceptibility of filamentous fungi to copper nanoparticles assessed by rapid XTT colorimetry and agar dilution method. Journal de mycologie medicale, 22(4), 322-328. https://doi.org/10.1016/j.mycmed.2012.09.006

Gontero, D., Lessard-Viger, M., Brouard, D., Bracamonte, A.G., Boudreau, D. and Veglia, A.V., 2017. Smart multifunctional nanoparticles design as sensors and drug delivery systems based on supramolecular chemistry. Microchemical Journal 130: 316–328. https://doi.org/10.1016/j.microc.2016.10.007

Gonzalez-Jartín, J.M., de Castro Alves, L., Alfonso, A., Pineiro, Y., Vilar, S.Y., Gomez, M.G., et al., 2019. Detoxification agents based on magnetic nanostructured particles as a novel strategy for mycotoxin mitigation in food. Food Chemistry 294: 60–66. https://doi.org/10.1016/j.foodchem.2019.05.013

Goryacheva, I.Y. and De Saeger, S., 2012. Immunochemical detection of masked mycotoxins: a short review. World Mycotoxin Journal 5: 281–287. https://doi.org/10.3920/WMJ2012.1423

Goud, K.Y., Kailasa, S.K., Kumar, V., Tsang, Y.F., Gobi, K.V. and Kim, K.-H., 2018. Progress on nanostructured electrochemical sensors and their recognition elements for detection of mycotoxins: a review. Biosensors and Bioelectronics 121: 205–222. https://doi.org/10.1016/j.bios.2018.08.029

Goud, K.Y., Reddy, K.K., Satyanarayana, M., Kummari, S. and Gobi, K.V., 2019. A review on recent developments in optical and electrochemical aptamer-based assays for mycotoxin susing advanced nanomaterials. Microchimica Acta 187(1): 2–9. https://doi.org/10.1007/s00604-019-4034-0

Grusie, T., Cowan, V., Singh, J., McKinnon, J. and Blakley, B., 2018. Proportions of predominant Ergot alkaloids (*Claviceps purpurea*) detected in western Canadian grains from 2014 to 2016. World Mycotoxin Journal 11(2): 259–264. https://doi.org/10.3920/WMJ2017.2241

Guo, L.J., Feng, J.S., Fang, Z.C., Xu, J. and Lu, X.N., 2015. Application of microfluidic 'lab-on-a-chip' for the detection of mycotoxins in foods. Trends in Food Science and Technology 46: 252–263. https://doi.org/10.1016/j.tifs.2015.09.005

Hamad, G.M., Mehany, T., Simal-Gandara, J., Abou-Alella, S., Esua, O.J., Abdel-Wahhab, M.A. and Hafez, E.E., 2022. A review of recent innovative strategies for controlling mycotoxins in foods. Food Control 144: 109350. https://doi.org/10.1016/j.foodcont.2022.109350

Han, X., Huangfu, B., Xu, T., Xu, W., Asakiya, C., Huang, K. and He, X., 2022. Research progress of safety of zearalenone: a review. Toxins 14(6): 386. https://doi.org/10.3390/toxins14060386

Han, Z., Jiang, K., Fan, Z., Diana Di Mavungu, J., Dong, M., Guo, W., et al., 2017. Multi-walled carbon nanotubes-based magnetic solid-phase extraction for the determination of zearalenone and its derivatives in maize by ultra-high performance liquid chromatography-tandem mass spectrometry. Food Control 79: 177–184. https://doi.org/10.1016/j.foodcont.2017.03.044

Haque, M.A., Wang, Y., Shen, Z., Li, X., Saleemi, M.K. and He, C., 2020. Mycotoxin contamination and control strategy in human, domestic animal and poultry: a review. Microbial Pathogenesis 142: 104095. https://doi.org/10.1016/j.micpath.2020.104095

Hashem, A.H., Abdelaziz, A.M., Askar, A.A., Fouda, H.M., Khalil, A.M., Abd-Elsalam, K.A. and Khaleil, M.M., 2021. Bacillus megaterium-mediated synthesis of selenium nanoparticles and their antifungal activity against Rhizoctonia solaniin faba bean plants. Journal of Fungi 7(3): 195. https://doi.org/10.3390/jof7030195

Hassanzadeh Davarani, F., Ashrafizadeh, M., Saberi Riseh, R., Ghasemipour Afshar, E., Mohammadi, H., Razavi, S.H., et al., 2018. Antifungal nanoparticles reduce aflatoxin contamination in pistachio. Journal of Pistachio and Health 1(2): 26–33.

Hawar, S.N., Al-Shmgani, H.S., Al-Kubaisi, Z.A., Sulaiman, G.M., Dewir, Y.H. and Rikisahedew, J.J., 2022. Green synthesis of silver nanoparticles from Alhagi graecorum leaf extract and evaluation of their cytotoxicity and antifungal activity. Journal of Nanomaterials 2022: 1–8. https://doi.org/10.1155/2022/1058119

He, L., Liu, Y., Mustapha, A., & Lin, M. (2011). Antifungal activity of zinc oxide nanoparticles against *Botrytis cinerea* and *Penicillium expansum*. Microbiological research, 166(3), 207-215. https://doi.org/10.1016/j.micres.2010.03.003

Henam, S.D., Ahmad, F., Shah, M.A., Parveen, S. and Wani, A.H., 2019. Microwave synthesis of nanoparticles and their antifungal activities. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy 213: 337–341. https://doi.org/10.1016/j.saa.2019.01.071

Horky, P., Skalickova, S., Baholet, D. and Skladanka, J., 2018. Nanoparticles as a solution for eliminating the risk of mycotoxins. Nanomaterials 8(9): 727. https://doi.org/10.3390/nano8090727

Huang, L., Chen, K., Zhang, W., Zhu, W., Liu, X. and Wang, J., 2018. ssDNA-tailorable oxidase-mimicking activity of spinel $MnCo_2O_4$ for sensitive biomolecular detection in food sample. Sensors and Actuators B: Chemical 269: 79–87. https://doi.org/10.1016/j.snb.2018.04.150

Huang, Z., He, J., Li, Y., Wu, C., You, L., Wei, H., et al., 2019. Preparation of dummy molecularly imprinted polymers for extraction of Zearalenonein grain samples. Journal of Chromatography A 1602: 11–18. https://doi.org/10.1016/j.chroma.2019.05.022

Hulvova, H., Galuszka, P., Frebortova, J. and Frebort, I., 2013. Parasitic fungus Claviceps as a source for biotechnological production of ergot alkaloids. Biotechnology Advances 31(1): 79–89. https://doi.org/10.1016/j.biotechadv.2012.01.005

Hussain, A., Rahman, Z. and Khan, M. 2021. Detection of aflatoxins in peanut oils marketed in Peshawar, Pakistan using thin layer chromatography. Journal of Food Quality and Hazards Control, 8: 87–91. https://doi.org/10.18502/jfqhc.8.2.6473

Hussein, H.S. and Brasel, J.M., 2001. Toxicity, metabolism and impact of mycotoxins on humans and animals. Toxicology 167(2): 101–134. https://doi.org/10.1016/S0300-483X(01)00471-1

Huybrechts, B., Martins, J.C., Debongnie, P., Uhlig, S. and Callebaut, A., 2015. Fast and sensitive LC-MS/MS method measuring human mycotoxin exposure using biomarkers in urine. Archives of Toxicology 89: 1993–2005. https://doi.org/10.1007/s00204-014-1358-8

Ismail, A., Gonçalves, B.L., de Neeff, D.V., Ponzilacqua, B., Coppa, C.F.S.C., Hintzsche, H., et al., 2018. Aflatoxin in foodstuffs: occurrence and recent advances in decontamination. Food Research International 113: 74–85. https://doi.org/10.1016/j.foodres.2018.06.067

Jamil, T.S., Abbas, H.A., Nasr, R.A., El-Kady, A.A. and Ibrahim, M.I.M., 2017. Detoxification of aflatoxin B1 using nano-sized Sc-doped $SrTi0.7Fe0.3O_3$ under visible light. Journal of Photochemistry and Photo Biology A: Chemistry 341: 127–135. https://doi.org/10.1016/j.jphotochem.2017.03.023

Jard, G., Liboz, T., Mathieu, F., Guyonvarch, A. and Lebrihi, A., 2011. Review of mycotoxin reduction in food and feed: from prevention in the field to detoxification by adsorption or transformation. Food Additives & Contaminants: Part A 28(11): 1590–1609. https://doi.org/10.1080/19440049.2011.595377

Jestoi, M. (2008). Emerging Fusarium-mycotoxins fusaproliferin, beauvericin, enniatins, and moniliformin—A review. Critical reviews in food science and nutrition, 48(1), 21-49. https://doi.org/10.1080/10408390601062021

Jian, Y., Chen, X., Ahmed, T., Shang, Q., Zhang, S., Ma, Z. and Yin, Y., 2022. Toxicity and action mechanisms of silver nanoparticles against the mycotoxin-producing fungus Fusarium graminearum. Journal of Advanced Research 38: 1–12. https://doi.org/10.1016/j.jare.2021.09.006

Jiang, M., Braiek, M., Florea, A., Chrouda, A., Farre, C., Bonhomme, A., et al., 2015. Aflatoxin B1 detection using a highly-sensitive molecularly-imprinted electrochemical sensor based on an electro polymerized metal organic framework. Toxins 7(9): 3540–3553. https://doi.org/10.3390/toxins7093540

Jiang, C., Lan, L., Yao, Y., Zhao, F. and Ping, J., 2018. Recent progress in application of nanomaterial-enabled biosensors for ochratoxin A detection. TrAC Trends in Analytical Chemistry 102: 236–249. https://doi.org/10.1016/j.trac.2018.02.007

Jing, G., Wang, Y., Wu, M., Liu, W., Xiong, S., Yu, J., et al., 2023. Photocatalytic degradation and pathway from mycotoxins in food: a review. Food Reviews International ,40(1): 276–292. https://doi.org/10.1080/87559129.2023.2166062

Kamle, M., Mahato, D.K., Gupta, A., Pandhi, S., Sharma, N., Sharma, B., et al., 2022. Citrinin mycotoxin contamination in food and feed: impact on agriculture, human health, and detection and management strategies. Toxins 14(2): 85. https://doi.org/10.3390/toxins14020085

Kanhed, P., Birla, S., Gaikwad, S., Gade, A., Seabra, A.B., Rubilar, O., et al., 2014. *In vitro* antifungal efficacy of copper nanoparticles against selected crop pathogenic fungi. Materials Letters 115: 13–17. https://doi.org/10.1016/j.matlet.2013.10.011

Karami-Osboo, R., Maham, M. and Mirabolfathy, M., 2015. Magnetic nanoparticle solid phase extraction-HPLC-UV for determination of deoxynivalenolin wheat flour. Analytical Methods 7(24): 10266–10271. https://doi.org/10.1039/C5AY02502H

Karami-Osboo, R. and Mirabolfathi, M., 2017. A novel dispersive nanomagnetic particle solid-phase extraction method to determine aflatoxins in nut and cereal samples. Food Analytical Methods10(12): 4086–4093. https://doi.org/10.1007/s12161-017-0975-2

Kaushik, A., Solanki, P. R., Ansari, A. A., Ahmad, S., & Malhotra, B. D. (2009). A nanostructured cerium oxide film-based immunosensor for mycotoxin detection. Nanotechnology, 20(5), 055105. https://doi.org/10.1088/0957-4484/20/5/055105

Khalil, O.A.A., Hammad, A.A. and Sebaei, A.S., 2021. Aspergillus flavus and Aspergillus ochraceus inhibition and reduction of aflatoxins and ochratoxin A in maize by irradiation. Toxicon 198: 111–120. https://doi.org/10.1016/j.toxicon.2021.04.029

Khalili, S.T., Mohsenifar, A., Beyki, M., Zhaveh, S., Rahmani-Cherati, T., Abdollahi, A., et al., 2015. Encapsulation of thyme essential oils in chitosan-benzoic acid nanogel with enhanced antimicrobial activity against Aspergillus flavus. LWT – Food Science and Technology 60(1): 502–508. https://doi.org/10.1016/j.lwt.2014.07.054

Khamis, Y., Hashim, A.F., Margarita, R., Alghuthaymi, M.A. and Abd-Elsalam, K.A. 2017. Fungicidal efficacy of chemically produced copper nanoparticles against penicillium digitatum and fusarium solanion citrus fruit. Philippine Agricultural Scientist 100: 69–78.

Khaneghah, A.M., Fakhri, Y., Gahruie, H.H., Niakousari, M. and Santana, A.S., 2019. Mycotoxins in cereal-based products during 24 years (1983–2017): a global systematic review. Trends in Food Science & Technology 91: 95–105. https://doi.org/10.1016/j.tifs.2019.06.007

Koka, J.A., Wani, A.H. and Bhat, M.Y., 2019. Evaluation of antifungal activity of magnesium oxide (MgO) and iron oxide (FeO)

nanoparticles on rot causing fungi. Journal of Drug Delivery and Therapeutics 9(2-s): 173–178.

Kong, D., Liu, L., Song, S., Suryoprabowo, S., Li, A., Kuang, H., Wang, L. and Xu, C., 2016. A gold nanoparticle-based semi-quantitative and quantitative ultrasensitive paper sensor for the detection of twenty mycotoxins. Nanoscale 8: 5245–5253. https://doi.org/10.1039/C5NR09171C

Kotzybik, K., Gräf, V., Kugler, L., Stoll, D. A., Greiner, R., Geisen, R., & Schmidt-Heydt, M. (2016). Influence of different nanomaterials on growth and mycotoxin production of Penicillium verrucosum. PLoS One, 11(3), e0150855. https://doi.org/10.1371/journal.pone.0150855

Krstanovic, V., Šarkanj, B., Velic, N., Mastanjevic, K., Šantek, B., & Mastanjevic, K. (2017). Mycotoxins in malting and brewing by-products used for animal feed. In European Biotechnology Congress 2017 (pp. S68-S69). https://doi.org/10.1016/j.jbiotec.2017.06.1033

Kumar, P., Mahato, D.K., Kamle,M., Mohanta, T.K. and Kang, S.G., 2017. Aflatoxins: a global concern for food safety, human health and their management. Frontiers in Microbiology 7: 2170. https://doi.org/10.3389/fmicb.2016.02170

Laan, T.T., Bull, S., Pirie, R. and Fink-Gremmels, J., 2006. The role of alveolar macrophages in the pathogenesis of recurrent airway obstruction in horses. Journal of Veterinary Internal Medicine 20(1): 167–174. https://doi.org/10.1111/j.1939-1676.2006.tb02837.x

Li, N., Wu, D., Hu, N., Fan, G., Li, X., Sun, J., *et al.*, 2018. Effective enrichment and detection of trace polycyclic aromatic hydrocarbons in food samples based on magnetic covalent organic framework hybrid microspheres. Journal of Agricultural and Food Chemistry 66(13): 3572–3580. https://doi.org/10.1021/acs.jafc.8b00869

Li, G., Zhang, X., Zheng, F., Liu, J. and Wu, D., 2020. Emerging nanosensing technologies for the detection of β-agonists. Food Chemistry 332: 127431. https://doi.org/10.1016/j.foodchem.2020.127431

Liang, H., Xu, H., Zhao, Y., Zheng, J., Zhao, H., Li, G., and Li, C. P. (2019). Ultrasensitive electrochemical sensor for prostate specific antigen detection with a phosphorene platform and magnetic covalent organic framework signal amplifier. Biosensors and Bioelectronics, 144, 111691. https://doi.org/10.1016/j.bios.2019.111691

Liew, W.P.P. and Mohd-Redzwan, S., 2018. Mycotoxin: its impact on gut health and microbiota. Frontiers in Cellular and Infection Microbiology 8: 60. https://doi.org/10.3389/fcimb.2018.00060

Lin, X., Yu, W., Tong, X., Li, C., Duan, N., Wang, Z. and Wu, S. 2024. Application of nanomaterials for coping with mycotoxin contamination in food safety: from detection to control. Critical Reviews in Analytical Chemistry 54(2): 355–388. https://doi.org/10.1080/10408347.2022.2076063

Liu, Z., Hua, Q., Wang, J., Liang, Z., Li, J., Wu, J., et al., 2020. A smart phone based dual detection mode device integrated with two lateral flow immunoassays for multiplex mycotoxins in cereals. Biosensors and Bioelectronics 158: 112178. https://doi.org/10.1016/j.bios.2020.112178

Loi, M., Logrieco, A.F., Pusztahelyi, T., Leiter, E., Hornok, L. and Pocsi, I. 2023. Advanced mycotoxin control and decontamination techniques in view of an increased aflatoxin risk in Europe due to climate change. Frontiers in Microbiology 13: 1085891. https://doi.org/10.3389/fmicb.2022.1085891

Loi, M., Renaud, J.B., Rosini, E., Pollegioni, L., Vignali, E., Haidukowski, M., et al., 2020. Enzymatic transformation of aflatoxin B1 by Rh_DypB peroxidase and characterization of the reaction products. Chemosphere 250: 126296. https://doi.org/10.1016/j.chemosphere.2020.126296

Luo, Y., Liu, X. and Li, J., 2018. Updating techniques on controlling mycotoxins—a review. Food Control 89: 123–132. https://doi.org/10.1016/j.foodcont.2018.01.016

Luo, L., Liu, X., Ma, S., Li, L. and You, T. 2020. Quantification of zearalenone in mildewing cereal crops using an innovative photoelectrochemical aptamer sensing strategy based on ZnO-NGQDs composites. Food Chemistry 322: 126778. https://doi.org/10.1016/j.foodchem.2020.126778

Luo, Y., Zhou, Z. and Yue, T., 2017. Synthesis and characterization of nontoxic chitosan-coated Fe_3O_4 particles for patulin adsorption in a juice-pH simulation aqueous. Food Chemistry 221: 317–323. https://doi.org/10.1016/j.foodchem.2016.09.008

Lv, M., Liu, Y., Geng, J., Kou, X., Xin, Z. and Yang, D., 2018. Engineering nanomaterials-based biosensors for food safety detection. Biosensors and Bioelectronics 106: 122–128. https://doi.org/10.1016/j.bios.2018.01.049

Madalena, M., Sobral, C., Faria, M. A., Cunha, S. C., & Ferreira, I. M. P. L. V. O. (2018). Toxicological interactions between mycotoxins from ubiquitous fungi: impact on hepatic and intestinal human epithelial cells. 202: 538–548. https://doi.org/10.1016/j.chemosphere.2018.03.122

Mahato, D.K., Pandhi, S., Kamle, M., Gupta, A., Sharma, B., Panda, B.K., et al., 2022. Trichothecenes in food and feed: occurrence, impact on human health and their detection and management strategies. Toxicon 208: 62–77. https://doi.org/10.1016/j.toxicon.2022.01.011

Mantle, P., 2002. Risk assessment and the importance of ochratoxins. International Biodeterioration & Biodegradation 50(3–4*):* 143–146. https://doi.org/10.1016/S0964-8305(02)00079-3

Mao, J., Zhang, Q., Li, P., Zhang, L., & Zhang, W. (2018). Geometric architecture design of ternary composites based on dispersive WO3 nanowires for enhanced visible-light-driven activity of refractory pollutant degradation. Chemical Engineering Journal, 334, 2568-2578. https://doi.org/10.1016/j.cej.2017.10.165

Marin, S., Ramos, A.J., Cano-Sancho, G. and Sanchis, V., 2013. Mycotoxins: occurrence, toxicology, and exposure assessment. Food and Chemical Toxicology 60: 218–237. https://doi.org/10.1016/j.fct.2013.07.047

Massart, F., Meucci, V., Saggese, G. and Soldani, G. 2008. High growth rate of girls with precocious puberty exposed to estrogenic mycotoxins. Journal of Pediatrics 152(5*):* 690–695, e691. https://doi.org/10.1016/j.jpeds.2007.10.020

Meira, D.I., Barbosa, A.I., Borges, J., Reis, R.L., Correlo, V.M. and Vaz, F., 2023. Recent advances in nanomaterial-based optical biosensors for food safety applications: ochratoxin-A detection, as case study. Critical Reviews in Food Science and Nutrition 64(18): 6318–6360. https://doi.org/10.1080/10408398.2023.2168248

Mogensen, J.M., Frisvad, J.C., Thrane, U. and Nielsen, K.F., 2010. Production of fumonisin B2 and B4 by Aspergillus niger on grapes and raisins. Journal of Agricultural and Food Chemistry 58(2*):* 954–958. https://doi.org/10.1021/jf903116q

Mohammadi, X., Matinfar, G., Khaneghah, A.M., Singh, A. and Pratap-Singh, A, 2021. Emergence of cold plasma and electron beam irradiation as novel technologies to counter mycotoxins in food products. World Mycotoxin Journal 14: 75–83. https://doi.org/10.3920/WMJ2020.2586

Moreno, V., Zougagh, M., & Ríos, Á. (2016). Hybrid nanoparticles based on magnetic multiwalled carbon nanotube-nanoC 18 SiO 2 composites for solid phase extraction of mycotoxins prior to their determination by LC-MS. Microchimica Acta, 183, 871–880. https://doi.org/10.1007/s00604-015-1722-2

Moreno-Vargas, J.M., Echeverry-Cardona, L.M., Moreno-Montoya, L.E. and Restrepo-Parra, E., 2023. Evaluation of antifungal activity of Ag nanoparticles synthetized by green chemistry against Fusarium solani and Rhizopus stolonifera. Nanomaterials 13(3): 548. https://doi.org/10.3390/nano13030548

Mukherjee, K., Acharya, K., Biswas, A. and Jana, N.R., 2020. TiO_2 nanoparticles co-doped with nitrogen and fluorine as visible-light activated antifungal agents. ACS Applied Nano Materials 3(2): 2016–2025. https://doi.org/10.1021/acsanm.0c00108

Mukunzi, D., Habimana, J.D.D., Li, Z. and Zou, X., 2022. Mycotoxins detection: view in the lens of molecularly imprinted polymer and nanoparticles. Critical Reviews in Food Science and Nutrition 63(23): 6034–6068. https://doi.org/10.1080/10408398.2022.2027338

Munkvold, G.P., 2017. Fusarium species and their associated mycotoxins. Mycotoxigenic fungi. Springer, Cham, Switzerland, pp. 51–106. https://doi.org/10.1007/978-1-4939-6707-0_4

Nabawy, G. A., Hassan, A. A., Sayed El-Ahl, R., & Refai, M. K. (2014). Effect of metal nanoparticles in comparison with commercial antifungal feed additives on the growth of *Aspergillus flavus* and aflatoxin b1 production. J. Glob. Biosci, 3(6), 954–971.

Nahle, S., El Khoury, A., Savvaidis, I., Chokr, A., Louka, N. and Atoui, A. 2022. Detoxification approaches of mycotoxins: by microorganisms, biofilms and enzymes. International Journal of Food Contamination 9: 1–14. https://doi.org/10.1186/s40550-022-00089-2

Nakagawa, H., Ohmichi, K., Sakamoto, S., Sago, Y., Kushiro, M., Nagashima, H., et al., 2011. Detection of a new fusarium masked mycotoxin in wheat grain by high-resolution LC-Orbit rap TM MS. Food Additives & Contaminants. Part A, Chemistry, Analysis, Control, Exposure & Risk Assessment 28: 1447–1456. https://doi.org/10.1080/19440049.2011.597434

Niazi, S., Khan, I. M., Yan, L., Khan, M. I., Mohsin, A., Duan, N., ... & Wang, Z. (2019). Simultaneous detection of fumonisin B 1 and ochratoxin A using dual-color, time-resolved luminescent nanoparticles (NaYF 4: Ce, Tb and NH 2-Eu/DPA@ SiO 2) as labels. Analytical and bioanalytical chemistry, 411, 1453-1465. https://doi.org/10.1007/s00216-019-01580-0

Niemirowicz, K., & Bucki, R. (2017). Enhancing the fungicidal activity of antibiotics: are magnetic nanoparticles the key?. Nanomedicine, 12(15), 1747-1749. https://doi.org/10.2217/nnm-2017-0051

Niemirowicz, K., Durnaś, B., Piktel, E., & Bucki, R. (2017). Development of antifungal therapies using nanomaterials. Nanomedicine, 12(15), 1891-1905. https://doi.org/10.2217/nnm-2017-0052

Niu, X., Cheng, N., Ruan, X., Du, D. and Lin, Y., 2019. Review-nanozyme-based immunosensors and immunoassays: recent developments and future trends. Journal of the Electrochemical Society 167(3): 037508. https://doi.org/10.1149/2.0082003JES

Omotayo, O.P., Omotayo, A.O., Mwanza, M. and Babalola, O.O., 2019. Prevalence of mycotoxins and their consequences on human health. Toxicological Research 35: 1–7. https://doi.org/10.5487/TR.2019.35.1.001

Osweiler, G.D., 2000. Mycotoxins—contemporary issues of food animal health and productivity. Veterinary Clinics of North America – Food Animal Practice 16: 511–530. https://doi.org/10.1016/S0749-0720(15)30084-0

Pacheco, J.G., Castro, M., Machado, S., Barroso, M.F., Nouws, H.P. and Delerue-Matos, C., 2015. Molecularly imprinted electrochemical sensor for ochratoxin A detection in food samples. Sensors and Actuators B: Chemical 215: 107–112. https://doi.org/10.1016/j.snb.2015.03.046

Pandey, A.K., Shakya, S., Patyal, A., Ali, S.L., Bhonsle, D., Chandrakar, C., Kumar, A., Khan, R. and Hattimare, D. 2021. Detection of aflatoxin M1 in bovine milk from different agro-climatic zones of Chhattisgarh, India, using HPLC-FLD and assessment of human health risks. Mycotoxin Research 37: 265–273. https://doi.org/10.1007/s12550-021-00437-9

Pandiselvam, R., Sunoj, S., Manikantan, M.R., Kothakota, A. and Hebbar, K.B., 2017. Application and kinetics of ozone in food preservation. Ozone: Science & Engineering 39(2): 115–126. https://doi.org/10.1080/01919512.2016.1268947

Pankaj, S. K., Shi, H., and and Keener, K. M., 2018. A review of novel physical and chemical decontamination technologies for aflatoxin in food. Trends in Food Science & Technology, 71:, 73–83. https://doi.org/10.1016/j.tifs.2017.11.007

Parveen, S., Wani, A. H., Shah, M. A., Devi, H. S., Bhat, M. Y., & Koka, J. A. (2018). Preparation, characterization and antifungal activity of iron oxide nanoparticles. Microbial pathogenesis, 115, 287-292. https://doi.org/10.1016/j.micpath.2017.12.068

Petrakova, A.V., Urusov, A.E., Zherdev, A.V., Liu, L., Xu, C. and Dzantiev, B.B., 2017. Application of magnetite nanoparticles for the development of highly sensitive immuno chromatographic test systems for mycotoxin detection. Applied Biochemistry and Microbiology 53: 470–475. https://doi.org/10.1134/S0003683817040111

Pfeiffer, C., Rehbock, C., Hühn, D., Carrillo-Carrion, C., de Aberasturi, D. J., Merk, V., ... & Parak, W. J. (2014). Interaction of colloidal nanoparticles with their local environment: the (ionic) nanoenvironment around nanoparticles is different from bulk and determines the physico-chemical properties of the nanoparticles. Journal of The Royal Society Interface, 11(96), 20130931. https://doi.org/10.1098/rsif.2013.0931

Pitt, J., 2000. Toxigenic fungi: which are important. Sabouraudia 38(Supplement 1): 17–22. https://doi.org/10.1080/744118728

Piotrowska, M. 2021. Microbiological decontamination of mycotoxins: opportunities and limitations. Toxins 13: 819. https://doi.org/10.3390/toxins13110819

Qu, L., Wang, L., Ji, H., Fang, Y., Lei, P., Zhang, X., et al., 2022. Toxic mechanism and biological detoxification of fumonisins. Toxins 14(3): 182. https://doi.org/10.3390/toxins14030182

Quintela, S., Villaran, M.C., Lopez de Armentia, I. and Elejalde, E. 2013. Ochratoxin A removal in wine: a review. Food Control 30: 439–445. https://doi.org/10.1016/j.foodcont.2012.08.014

Rai, M., Jogee, P.S. and Ingle, A.P., 2015. Emerging nanotechnology for detection of mycotoxins in food and feed. International Journal of Food Sciences and Nutrition 66(4): 363–370. https://doi.org/10.3109/09637486.2015.1034251

Ramadan, M.M., Mohamed, M.A., Almoammar, H. and Abd-Elsalam, K.A., 2020. Magnetic nanomaterials for purification, detection, and control of mycotoxins. In: Rai, M. and Abd-Elsalam, K.A. (eds.), Nanomycotoxicology. Elsevier, Amsterdam, the Netherlands, Chap. 5, pp. 87–114. https://doi.org/10.1016/B978-0-12-817998-7.00005-7

Rashed, A. O. M., Mohamed, A. E. A. A. R., & Abobakr, M. M. (2016). Wheat Protection from Root Rot Caused by *Fusarium culmorum* Using Silver Nanoparticles. Journal of the Chemical Society of Pakistan, 38(5), 898–903.

Rheeder, J.P., Marasas, W.F. and Vismer, H.F., 2002. Production of fumonisin analogs by Fusarium species. Applied and Environmental Microbiology 68(5): 2101–2105. https://doi.org/10.1128/AEM.68.5.2101-2105.2002

Rhouati, A., Bulbul, G., Latif, U., Hayat, A., Li, Z.-H. and Marty, J.L., 2017. Nano-aptasensing in mycotoxin analysis: recent updates and progress. Toxins 9(11): 349. https://doi.org/10.3390/toxins9110349

Rodrigues, I., 2014. A review on the effects of mycotoxins in dairy ruminants. Animal Production Science 54: 1155–1165. https://doi.org/10.1071/AN13492

Romero Bernal, A.R., Reynoso, C.M., Garcia Londono, V.A., Broggi, L.E. and Resnik, S.L., 2019. Alternaria toxins in Argentinean wheat, bran, and flour. Food Additives & Contaminants: Part B 12(1): 24–30. https://doi.org/10.1080/19393210.2018.1509900

Roque, L., Molpeceres, J., Reis, C., Rijo, P. and Pinto Reis, C., 2017. Past, recent progresses and future perspectives of nanotechnology applied to antifungal agents. Current Drug Metabolism 18(4): 280–290. https://doi.org/10.2174/1389200218666170201152000

Sadhasivam, S., Britzi, M., Zakin, V., Kostyukovsky, M., Trostanetsky, A., Quinn, E. and Sionov, E., 2017 Rapid detection and identification of mycotoxigenic fungi and mycotoxins in stored wheat grain. Toxins 9: 302. https://doi.org/10.3390/toxins9100302

Sadrabadi, N.R., Ensafi, A.A., Heydari-Bafrooei, E. and Fazilati, M., 2016. Screening of food samples for zearalenone toxin using an electrochemical bioassay based on DNA–zearalenon interaction. Food Analytical Methods 9: 2463–2470. https://doi.org/10.1007/s12161-016-0437-2

Samuel, M.S., Jeyaram, K., Datta, S., Chandrasekar, N., Balaji, R. and Selvarajan, E. 2021. Detection, contamination, toxicity, and prevention methods of ochratoxins: an update review. Journal of Agricultural and Food Chemistry 69: 13974–13989. https://doi.org/10.1021/acs.jafc.1c05994

Santana-Mayor, A., Rodríguez-Ramos, R., Socas-Rodríguez, B., AsensioRamos, M. and Rodríguez-Delgado, M.A., 2020. Carbon-based adsorbents. In: Solid-phase extraction: handbooks in separation science. Colin F. Poole (Ed.), Elsevier, Amsterdam, the Netherlands, Chap. 4, pp. 83–127. https://doi.org/10.1016/B978-0-12-816906-3.00004-2

Santini, A., Meca, G., Uhlig, S., & Ritieni, A. (2012). Fusaproliferin, beauvericin and enniatins: occurrence in food–a review. World Mycotoxin Journal, 5(1), 71–81. https://doi.org/10.3920/WMJ2011.1331

Savi, G.D., Torres Zanoni, E., Scussel, R., Corneo, E.D.S., Guimaraes Furtado, B., Macuvele, D.L.P., et al., 2023. Mesoporous silica nanoparticles adsorb aflatoxin B1 and reduce mycotoxin-induced cell damage. Journal of Environmental Science and Health, Part B 58(1): 1–9. https://doi.org/10.1080/03601234.2022.2161251

Selvaraj, J.N., Zhou, L., Wang, Y., Zhao, Y.J., Xing, F.G., Dai, X.F. and Liu, Y., 2015. Mycotoxin detection—recent trends at global level. Journal of Integrative Agriculture 14: 2265–2281. https://doi.org/10.1016/S2095-3119(15)61120-0

Shahbaz, M., Akram, A., Raja, N.I., Mukhtar, T., Mehak, A., Fatima, N., et al., 2023. Antifungal activity of green synthesized selenium nanoparticles and their effect on physiological, biochemical, and antioxidant defense system of mango under mango malformation disease. PLoS One 18(2): e0274679. https://doi.org/10.1371/journal.pone.0274679

Sharma, A., Matharu, Z., Sumana, G., Solanki, P.R., Kim, C.G. and Malhotra, B.D., 2010. Antibody immobilized cysteamine functionalized-gold nanoparticles for aflatoxin detection. Thin Solid Films 519(3): 1213–1218. https://doi.org/10.1016/j.tsf.2010.08.071

Sharma, R., Ragavan, K.V., Thakur, M.S. and Raghavarao, K.S.M.S., 2015. Recent advances in nanoparticle based apta sensors for food contaminants. Biosensors and Bioelectronics 74: 612–627. https://doi.org/10.1016/j.bios.2015.07.017

Shenashen, M., Derbalah, A., Hamza, A., Mohamed, A. and El Safty, S., 2017. Antifungal activity of fabricated mesoporous alumina nanoparticles against root rot disease of tomato caused by fusarium oxysporium. Pest Management Science 73: 1121–1126. https://doi.org/10.1002/ps.4420

Shende, S., Ingle, A. P., Gade, A., & Rai, M. (2015). Green synthesis of copper nanoparticles by *Citrus medica Linn.*(*Idilimbu*) juice and its antimicrobial activity. World Journal of Microbiology and Biotechnology, 31, 865–873. https://doi.org/10.1007/s11274-015-1840-3

Shoala, T., 2020. Carbon nanostructures: detection, controlling plant diseases and mycotoxins. In Abd-Elsalam, K.A. (ed.), Carbon nanomaterials for agri-food and environmental applications. Elsevier, Amsterdam, the Netherlands, Chap. 13, pp. 261–277. https://doi.org/10.1016/B978-0-12-819786-8.00013-X

Simpson, D.R., Weston, G.E., Turner, J.A., Jennings, P. and Nicholson, P., 2001. Differential control of head blight pathogens of wheat by fungicides and consequences for mycotoxin

contamination of grain. European Journal of Plant Pathology 107: 421–431. https://doi.org/10.1023/A:1011225817707

Santana-Mayor, A., Rodríguez-Ramos, R., Socas-Rodriguez, B., Asensio-Ramos, M., & Rodriguez-Delgado, M. A. (2020). Carbon-based adsorbents. In Solid-phase extraction (pp. 83-127). Elsevier. https://doi.org/10.21203/rs.3.rs-1908427/v1

Solanki, P.R., Singh, J., Rupavali, B., Tiwari, S. and Malhotra, B.D., 2017. Bismuth oxide nanorods based immunosensor for mycotoxin detection. Materials Science & Engineering, Materials for Biological Applications 70: 564–571. https://doi.org/10.1016/j.msec.2016.09.027

Stanford, K., Schwartzkopf-Genswein, K.S., Melendez, D.M., Ngo, S., Harding, M., McAllister, T.A., et al., 2022. Effects of heating, pelleting, and feed matrix on apparent concentrations of cereal ergot alkaloids in relation to growth performance and welfare parameters of backgrounding beef steers. Toxins 14(9): 580. https://doi.org/10.3390/toxins14090580

Stroka, J. and Maragos, C., 2016. Challenges in the analysis of multiple mycotoxins. World Mycotoxin Journal 9(5): 847–861. https://doi.org/10.3920/WMJ2016.2038

Su, Y., Wu, D., Chen, J., Chen, G., Hu, N., Wang, H., et al., 2019. Ratiometric surface enhanced raman scattering immunosorbent assay of allergenic proteins via covalentorganic frame work composite material based nanozyme tag triggered raman signal "turn-on" and amplification. Analytical Chemistry 91(18): 11687–11695. https://doi.org/10.1021/acs.analchem.9b02233

Suliman Maashi, M., 2023. CRISPR/CAS-based aptasensor as an innovative sensing approaches for food safety analysis: recent progresses and new horizons. Critical Reviews in Analytical Chemistry 53(1): 1–19. https://doi.org/10.1080/10408347.2023.2188955

Sun, Y., Xing, G., Yang, J., Wang, F., Deng, R., Zhang, G., et al., 2016. Development of an immunochromatographic test strip for simultaneous qualitative and quantitative detection of ochratoxin A and zearalenone in cereal. Journal of the Science of Food and Agriculture 96: 3673–3678. https://doi.org/10.1002/jsfa.7550

Sun, S., Zhao, R., Feng, S. and Xie, Y., 2018. Colorimetric zearalenone assay based on the use of an aptamer and of gold nanoparticles with peroxidase-like activity. Microchimica Acta 185(12): 535. https://doi.org/10.1007/s00604-018-3078-x

Sun, S., Zhao, R., Xie, Y. and Liu, Y., 2019. Photocatalytic degradation of aflatoxin B1 by activated carbon supported TiO_2 catalyst. Food Control 100: 183–188. https://doi.org/10.1016/j.foodcont.2019.01.014

Sun, Y., Huang, K., Long, M., Yang, S., & Zhang, Y. (2022). An update on immunotoxicity and mechanisms of action of six environmental mycotoxins. Food and Chemical Toxicology, 163, 112895. https://doi.org/10.1016/j.fct.2022.112895

Sureka, S., Chalcravorty, A., Holmes, E.C., Spassibojko, O., Bhatt, N., et al., 2014. Standardization of functional reporter and antibiotic resistance cassettes to facilitate the genetic engineering of filamentous fungi. ACS Synthetic Biology 3: 960–962. https://doi.org/10.1021/sb5000143

Taghdisi, S.M., Danesh, N.M., Beheshti, H.R., Ramezani, M. and Abnous, K., 2016. A novel fluorescent aptasensor based on gold and silica nanoparticles for the ultrasensitive detection of ochratoxin A. Nanoscale 8(6): 3439–3446. https://doi.org/10.1039/C5NR08234J

Tanaka, K., Sago, Y., Zheng, Y., Nakagawa, H. and Kushiro, M., 2007. Mycotoxins in rice. International Journal of Food Microbiology 119(1): 59–66. https://doi.org/10.1016/j.ijfoodmicro.2007.08.002

Thongprapai, P., Cheewasedtham, W., Chong, K. F., & Rujiralai, T. (2018). Selective magnetic nanographene oxide solid-phase extraction with high-performance liquid chromatography and fluorescence detection for the determination of zearalenone in corn samples. Journal of separation science, 41(23), 4348-4354. https://doi.org/10.1002/jssc.201800441

Tian, F., Zhou, J., Jiao, B. and He, Y.,2019. A nanozyme-based cascade colorimetric aptasensor for amplified detection of ochratoxin A. Nanoscale 11(19): 9547–9555. https://doi.org/10.1039/C9NR02872B

Tian, M., Feng, Y., He, X., Zhang, D., Wang, W., & Liu, D. (2022). Mycotoxins in livestock feed in China-Current status and future challenges. Toxicon, 214, 112-120. https://doi.org/10.1016/j.toxicon.2022.05.041

Tittlemier, S.A., Drul, D., Roscoe, M. and McKendry, T., 2015. Occurrence of ergot and ergot alkaloids in western Canadian wheat and other cereals. Journal of Agricultural and Food Chemistry 63(29): 6644–6650. https://doi.org/10.1021/acs.jafc.5b02977

Tola, M. and Kebede, B., 2016. Occurrence, importance and control of mycotoxins: a review. Cogent Food & Agriculture 2(1): 1191103. https://doi.org/10.1080/23311932.2016.1191103

Topi, D., Jakovac-Strajn, B., Pavsic-Vrtac, K. and Tavcar-Kalcher, G., 2017. Occurrence of ergot alkaloids in wheat from Albania. Food Additives & Contaminants: Part A 34(8): 1333–1343. https://doi.org/10.1080/19440049.2017.1307528

Turan, E. and ¸Sahin, F., 2016. Molecularly imprinted biocompatible magnetic nanoparticles for specific recognition of ochratoxin A. Sensors and Actuators B: Chemical 227: 668–676. https://doi.org/10.1016/j.snb.2015.12.087

Turner, N.W., Bramhmbhatt, H., Szabo-Vezse, M., Poma, A., Coker, R. and Piletsky, S.A., 2015. Analytical methods for determination of mycotoxins: an update (2009–2014). Analytica Chimica Acta 901: 12–33. https://doi.org/10.1016/j.aca.2015.10.013

Udovicki, B., Audenaert, K., De Saeger, S. and Rajkovic, A., 2018. Overview on the mycotoxins incidence in Serbia in the period 2004–2016. Toxins 10(7): 279. https://doi.org/10.3390/toxins10070279

Vidal, A., Ouhibi, S., Gali, R., Hedhili, A., De Saeger, S. and De Boevre, M., 2019. The mycotoxin patulin: an updated short review on occurrence, toxicity and analytical challenges. Food and Chemical Toxicology 129: 249–256. https://doi.org/10.1016/j.fct.2019.04.048

Vijayabharathi, R., Sathya, A. and Gopalakrishnan, S., 2018. Extracellular biosynthesis of silver nanoparticles using streptomyces griseoplanus SAI-25 and its antifungal activity against macrophominaphaseolina, the charcoal rot pathogen of sorghum. Biocatalysis and Agricultural Biotechnology 14: 166–171. https://doi.org/10.1016/j.bcab.2018.03.006

Walravens, J., Mikula, H., Rychlik, M., Asam, S., Ediage, E.N., Di Mavungu, J.D., et al., 2014. Development and validation of an ultra-high-performance liquid chromatography tandem mass spectrometric method for the simultaneous determination of free and conjugated alternaria toxins in cereal-based foodstuffs. Journal of Chromatography A 1372: 91–101. https://doi.org/10.1016/j.chroma.2014.10.083

Wan, H., Zhang, B., Bai, X. L., Zhao, Y., Xiao, M. W., & Liao, X. (2017). Extraction of ochratoxin A in red wine with dopamine-coated magnetic multi-walled carbon nanotubes. Journal of separation science, 40(20), 4022-4031. https://doi.org/10.1002/jssc.201700697

Wang, L., Chen, W., Ma, W., Liu, L., Ma, W., Zhao, Y., et al., 2011. Fluorescent strip sensor for rapid determination of toxins. Chemical Communications 47(5): 1574–1576. https://doi.org/10.1039/C0CC04032K

Wang, X., Niessner, R., Tang, D. and Knopp, D., 2016. Nanoparticle-based immunosensors and immunoassays for aflatoxins. Analytica Chimica Acta 912: 10–23. https://doi.org/10.1016/j.aca.2016.01.048

Wang, Y., Zhao, C., Zhang, D., Zhao, M., Zheng, D., Peng, M., et al., 2018. Simultaneous degradation of aflatoxin B1 and zearalenone by a microbial consortium. Toxicon 146: 69–76. https://doi.org/10.1016/j.toxicon.2018.04.007

Wen, A., Li, G., Wu, D., Yu, Y., Yang, Y., Hu, N., et al., 2020. Sulphonate functionalized covalent organic framework-based magnetic sorbent for effective solid phase extraction and determination of fluoroquinolones. Journal of Chromatography A 1612: 4606. https://doi.org/10.1016/j.chroma.2019.460651

Wen, H., Shi, H., Jiang, N., Qiu, J., Lin, F. and Kou, Y., 2023. Antifungal mechanisms of silver nanoparticles on mycotoxin producing rice false smut fungus. I Science 26(1): 105763. https://doi.org/10.1016/j.isci.2022.105763

Win, T.T., Khan, S. and Fu, P., 2020. Fungus-(Alternaria sp.)-mediated silver nanoparticles synthesis, characterization, and screening of antifungal activity against some phytopathogens. Journal of Nanotechnology 36(4): 1–9. https://doi.org/10.1155/2020/8828878

Winter, G. and Pereg, L., 2019. A review on the relation between soil and mycotoxins: effect of aflatoxin on field, food and finance. European Journal of Soil Science 70(4): 882–897. https://doi.org/10.1111/ejss.12813

Wu, C., He, J., Li, Y., Chen, N., Huang, Z., You, L., et al., 2018. Solid phase extraction of aflatoxins using an anosorbent consisting of a magnetized nanoporous carbon core coated with a molecularly imprinted polymer. Microchimica Acta 185(11): 515. https://doi.org/10.1007/s00604-018-3051-8

Wu, H.-C. and Santella, R., 2012. The role of aflatoxins in hepatocellular carcinoma. Hepatitis Monthly 12: e7238. https://doi.org/10.5812/hepatmon.7238

Wu, S., Wang, F., Li, Q., Wang, J., Zhou, Y., Duan, N., et al., 2020. Photocatalysis and degradation products identification of deoxynivalenol in wheat using upconversion nanoparticles@ TiO_2 composite. Food Chemistry 323(1): 126823. https://doi.org/10.1016/j.foodchem.2020.126823

Xie, Y.J., Yang, Y., Kong, W.J., Yang, S.H. and Yang, M.H., 2015. Application of nanoparticle probe-based lateral flow immunochromatographic assay in mycotoxins detection. Chinese Journal of Analytical Chemistry 43: 617–628. https://doi.org/10.1016/S1872-2040(15)60821-0

Xue, Z., Zhang, Y., Yu, W., Zhang, J., Wang, J., Wan, F., et al., 2019. Recent advances in aflatoxin B1 detection based on nanotechnology and nanomaterials – a review. Analytica Chimica Acta 1069: 1–27. https://doi.org/10.1016/j.aca.2019.04.032

Yang, Y., Li, G., Wu, D., Liu, J., Li, X., Luo, P., et al., 2020a. Recent advances on toxicity and determination methods of mycotoxins in foodstuffs. Trends in Food Science & Technology 96: 233–252. https://doi.org/10.1016/j.tifs.2019.12.021

Yang, Y., Li, G., Wu, D., Wen, A., Wu, Y. and Zhou, X., 2020b. β-Cyclodextrin/AuNPs-functionalized covalent organic framework-based magnetic sorbent for solid phase extraction and determination of sulfonamides. Microchimica Acta 187(5): 278. https://doi.org/10.1007/s00604-020-04257-z

Yang, C., & Peng, B. (2023). Biodegradation characteristics of patulin by *Saccharomyces cerevisiae* during fermentation. Food Control, 145, 109463. https://doi.org/10.1016/j.foodcont.2022.109463

Yang, X., Sun, Z., He, Z., Xie, X. and Liu, X., 2023. Combination of nanobody and peptidomimetic to develop novel immunoassay platforms for detecting ochratoxin A in cereals. Food Chemistry 429(15): 137018. https://doi.org/10.1016/j.foodchem.2023.137018

Yu, L., Ma, F., Zhang, L., & Li, P. (2019). Determination of aflatoxin B1 and B2 in vegetable oils using Fe3O4/rGO magnetic solid phase extraction coupled with high-performance liquid chromatography fluorescence with post-column photochemical derivatization. Toxins, 11(11), 621. https://doi.org/10.3390/toxins11110621

Zeng, X., Zhang, F., He, N., Zhang, B., Liu, X., & Li, X. (2016). ZnO nanoparticles of different shapes and their antimycotic property against penicillium and mucor. Nanoscience and Nanotechnology Letters, 8(8), 688-694. https://doi.org/10.1166/nnl.2016.2206

Zhai, W., Wei, D., Cao, M., Wang, Z. and Wang, M., 2023. Biosensors based on core–shell nanoparticles for detecting mycotoxins in food: a review. Food Chemistry 429(15): 136944. https://doi.org/10.1016/j.foodchem.2023.136944

Zhan, S., Hu, J., Li, Y., Huang, X. and Xiong, Y. 2021. Direct competitive ELISA enhanced by dynamic light scattering for the ultrasensitive detection of aflatoxin B1 in corn samples. Food Chemistry 342: 128327. https://doi.org/10.1016/j.foodchem.2020.128327

Zhang, W.J. and Li, G.X., 2004. Third-generation biosensors based on the direct electron transfer of proteins. Analytical Sciences 20: 603–609. https://doi.org/10.2116/analsci.20.603

Zhang, X., Li, G., Chen, G., Wu, D., Zhou, X. and Wu, Y., 2020. Single atom nanozymes: arising star for biosensing and biomedicine. Coordination Chemistry Reviews 418: 213376. https://doi.org/10.1016/j.ccr.2020.213376

Zhang, J., Liu, Y., Li, Q., Zhang, X. and Shang, J.K., 2013. Antifungal activity and mechanism of palladium-modified nitrogen-doped

titanium oxide photocatalyst on agricultural pathogenic fungi *fusarium graminearum*. ACS Applied Materials & Interfaces 5(21): 10953–10959. https://doi.org/10.1021/am4031196

Zhang, Y., Ouyang, B., Zhang, W., Guang, C., Xu, W. and Mu, W., 2023. An overview of chemical, physical and biological methods for zearalenone elimination: recent advances and future prospective. Food Control 154, 110011. https://doi.org/10.1016/j.foodcont.2023.110011

Zhang, W., Xiong, H., Chen, M., Zhang, X. and Wang, S., 2017a. Surface enhanced molecularly imprinted electrochemiluminescence sensor based on Ru@SiO_2 for ultrasensitive detection of fumonisin B1. Biosensors and Bioelectronics 96: 55–61. https://doi.org/10.1016/j.bios.2017.04.035

Zhang, X., Li, G., Wu, D., Li, X., Hu, N., Chen, J., . . . Wu, Y. (2019). Recent progress in the design fabrication of metal-organic frameworks-based nanozymes and their applications to sensing and cancer therapy. Biosensors and Bioelectronics, 137, 178–198. https://doi.org/10.1016/j.bios. 2019.04.061

Zhang, X., Yu, X., Wen, K., Li, C., Mujtaba Mari, G., Jiang, H., ... & Wang, Z. (2017). Multiplex lateral flow immunoassays based on amorphous carbon nanoparticles for detecting three fusarium mycotoxins in maize. Journal of agricultural and food chemistry, 65(36), 8063-8071. https://doi.org/10.1021/acs.jafc.7b02827

Zhao, Z., Liu, N., Yang, L., Wang, J., Song, S., Nie, D., et al., 2015b. Crosslinked chitosan polymers as generic adsorbents for simultaneous adsorption of multiple mycotoxins. Food Control 57: 362–369. https://doi.org/10.1016/j.foodcont.2015.05.014

Zhao, Y., Wan, L.-H., Bai, X.-L., Liu, Y.-M., Zhang, F.-P., Liu, Y.-M. and Liao, X., 2017b. Quantification of mycotoxins in vegetable oil by UPLC-MS/MS after magnetic solid-phase extraction. Food Additives & Contaminants: Part A 34(7): 1201–1210. https://doi.org/10.1080/19440049.2017.1319074

Zhao, J., Wang, L., Xu, D. and Lu, Z., 2017a. Involvement of ROS in nano silver caused suppression of aflatoxin production from Aspergillus flavus. RSC Advances 7(37): 23021–23026. https://doi.org/10.1039/C7RA02312J

Zhao, Y., Yang, Y., Luo, Y., Yang, X., Li, M. and Song, Q., 2015a. Double detection of mycotoxins based on sers labels embedded Ag@Au core-shell nanoparticles. ACS Applied Materials and Interfaces 7: 21780–21786. https://doi.org/10.1021/acsami.5b07804

Zhao, Z., Zhang, Z., Zhang, H. and Liang, Z., 2022. Small peptides in the detection of mycotoxins and their potential applications in mycotoxin removal. Toxins 14(11): 795. https://doi.org/10.3390/toxins14110795

Zhaveh, S., Mohsenifar, A., Beiki, M., Khalili, S. T., Abdollahi, A., Rahmani-Cherati, T., & Tabatabaei, M. (2015). Encapsulation of Cuminum cyminum essential oils in chitosan-caffeic acid nanogel with enhanced antimicrobial activity against *Aspergillus flavus*. Industrial Crops and Products, 69, 251-256. https://doi.org/10.1016/j.indcrop.2015.02.028

Zheng, F., Ke, W., Shi, L., Liu, H., & Zhao, Y. (2019). Plasmonic Au–Ag janus nanoparticle engineered ratiometric surface-enhanced raman scattering aptasensor for Ochratoxin A detection. Analytical Chemistry, 91(18), 11812-11820. https://doi.org/10.1021/acs.analchem.9b02469

Zhong, W., 2009. Nanomaterials in fluorescence-based biosensing. Analytical and Bioanalytical Chemistry, 394(1): 47–59. https://doi.org/10.1007/s00216-009-2643-x

Zhong, L., Carere, J., Lu, Z., Lu, F. and Zhou, T., 2018. Patulin in apples and apple-based food products: the burdens and the mitigation strategies. Toxins 10(11): 475. https://doi.org/10.3390/toxins10110475

Zhou, Y.,Wu, S.,Wang, F., Li, Q., He, C., Duan, N. and Wang, Z., 2020. Assessing the toxicity *in vitro* of degradation products from deoxynivalenol photocatalytic degradation by using up conversion nanoparticles@TiO_2 composite. Chemosphere 238: 124648. https://doi.org/10.1016/j.chemosphere.2019.124648