Heliyon 10 (2024) e28361

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

A comprehensive review of mycotoxins: Toxicology, detection, and effective mitigation approaches

Rahim Khan [a,*], Farooq Anwar [a,b,**], Farinazleen Mohamad Ghazali [a]

[a] Department of Food Science, Faculty of Food Science and Technology, Universiti Putra Malaysia, 43400, UPM, Serdang, Malaysia
[b] Institute of Chemistry, University of Sargodha, Sargodha, 40100, Pakistan

ARTICLE INFO

Keywords:
Mycotoxin contamination
Human health
ELISA
LFA
Biosensors
CAP
Polyphenols
NEOs
Emerging technologies

ABSTRACT

Mycotoxins, harmful compounds produced by fungal pathogens, pose a severe threat to food safety and consumer health. Some commonly produced mycotoxins such as aflatoxins, ochratoxin A, fumonisins, trichothecenes, zearalenone, and patulin have serious health implications in humans and animals. Mycotoxin contamination is particularly concerning in regions heavily reliant on staple foods like grains, cereals, and nuts. Preventing mycotoxin contamination is crucial for a sustainable food supply. Chromatographic methods like thin layer chromatography (TLC), gas chromatography (GC), high-performance liquid chromatography (HPLC), and liquid chromatography coupled with a mass spectrometer (LC/MS), are commonly used to detect mycotoxins; however, there is a need for on-site, rapid, and cost-effective detection methods. Currently, enzyme-linked immunosorbent assays (ELISA), lateral flow assays (LFAs), and biosensors are becoming popular analytical tools for rapid detection. Meanwhile, preventing mycotoxin contamination is crucial for food safety and a sustainable food supply. Physical, chemical, and biological approaches have been used to inhibit fungal growth and mycotoxin production. However, new strains resistant to conventional methods have led to the exploration of novel strategies like cold atmospheric plasma (CAP) technology, polyphenols and flavonoids, magnetic materials and nanoparticles, and natural essential oils (NEOs). This paper reviews recent scientific research on mycotoxin toxicity, explores advancements in detecting mycotoxins in various foods, and evaluates the effectiveness of innovative mitigation strategies for controlling and detoxifying mycotoxins.

1. Introduction

Mycotoxins are secondary metabolites synthesized by filamentous fungi, such as *Aspergillus*, *Fusarium*, and *Penicillium,* and can cause serious diseases in humans and animals [1]. Mycotoxin-producing fungi contaminate food and feed, leading to socio-economic and health implications [2–4]. Mycotoxin contamination is a global risk to food crops, including cereals, (corn, rice, wheat, barley), lentils, fruits, peanuts, almonds, walnuts, pistachios, coffee, cotton seeds, spices (pepper, paprika, ginger), and meat [5–7]. According to Mesterházy et al. [8] contamination with mycotoxins is responsible for the wastage of approximately 1.3 billion metric tons of food

* Corresponding author.
** Corresponding author. Department of Food Science, Faculty of Food Science and Technology, Universiti Putra Malaysia, 43400, UPM, Serdang, Malaysia.
E-mail addresses: sirifrahim1@yahoo.com (R. Khan), farooq@upm.edu.my (F. Anwar), farinazleen@upm.edu.my (F.M. Ghazali).

https://doi.org/10.1016/j.heliyon.2024.e28361
Received 6 July 2023; Received in revised form 19 January 2024; Accepted 21 January 2024
Available online 23 March 2024

annually, equivalent to one-third of global food production.

To date, around 400 mycotoxins have been discovered, with only 30 known to be harmful to humans and animals [1,9]. Some well-known mycotoxins include aflatoxins (AFs), ochratoxin A (OTA), *Alternaria* toxins (alternariol (AOH), alternariol monomethylether (AME), tentoxin (TEN) and altenuen (ALT), fumonisins (FMNs), trichothecenes (T-2/HT-2 toxins, deoxynivalenol (DON), nivalenol (NIV)), citrinin (CIT), zearalenone (ZEN), ergot alkaloids, and patulin (PAT). Among mycotoxins, AFs are particularly concerning as they are highly toxic and considered as Group 1 human carcinogens by the International Agency for Research on Cancer (IARC) [10,11].

Mycotoxins can also cause cancer, allergies, and organ toxicity [12]. The severity of their effects relies on the degree of exposure and their mutagenic and teratogenic effects. For instance, consuming certain fungal-contaminated foods can lead to various long-term health effects, including liver cancer, immune suppression (AFB_1, OTA), abdominal pain (DON), endocrine disruption (ZEN), stunted growth (T-2 toxin), and genotoxicity [13–16]. Long-term exposure to multiple mycotoxins may also result in synergistic health impacts [17,18]. Efficient and reliable mycotoxin detection is crucial for maintaining food safety and preventing health issues. Chromatographic techniques like gas chromatography (GC), high-performance liquid chromatography (HPLC), and liquid chromatography coupled with a mass spectrometer (LC/MS) are widely employed for mycotoxin determination. Nevertheless, these methodologies are not feasible for quick examination of raw materials owing to their high cost and the requisite for skilled workers [19,20].

To address this, some innovative detection methods, including enzyme-linked immunosorbent assay (ELISA), lateral flow assays (LFAs), and biosensors, have been devised to detect and quantify mycotoxins rapidly. Meanwhile, developing strategies for preventing and eliminating mycotoxins in food products is important. Some physical, chemical, and biological methods are traditionally used to

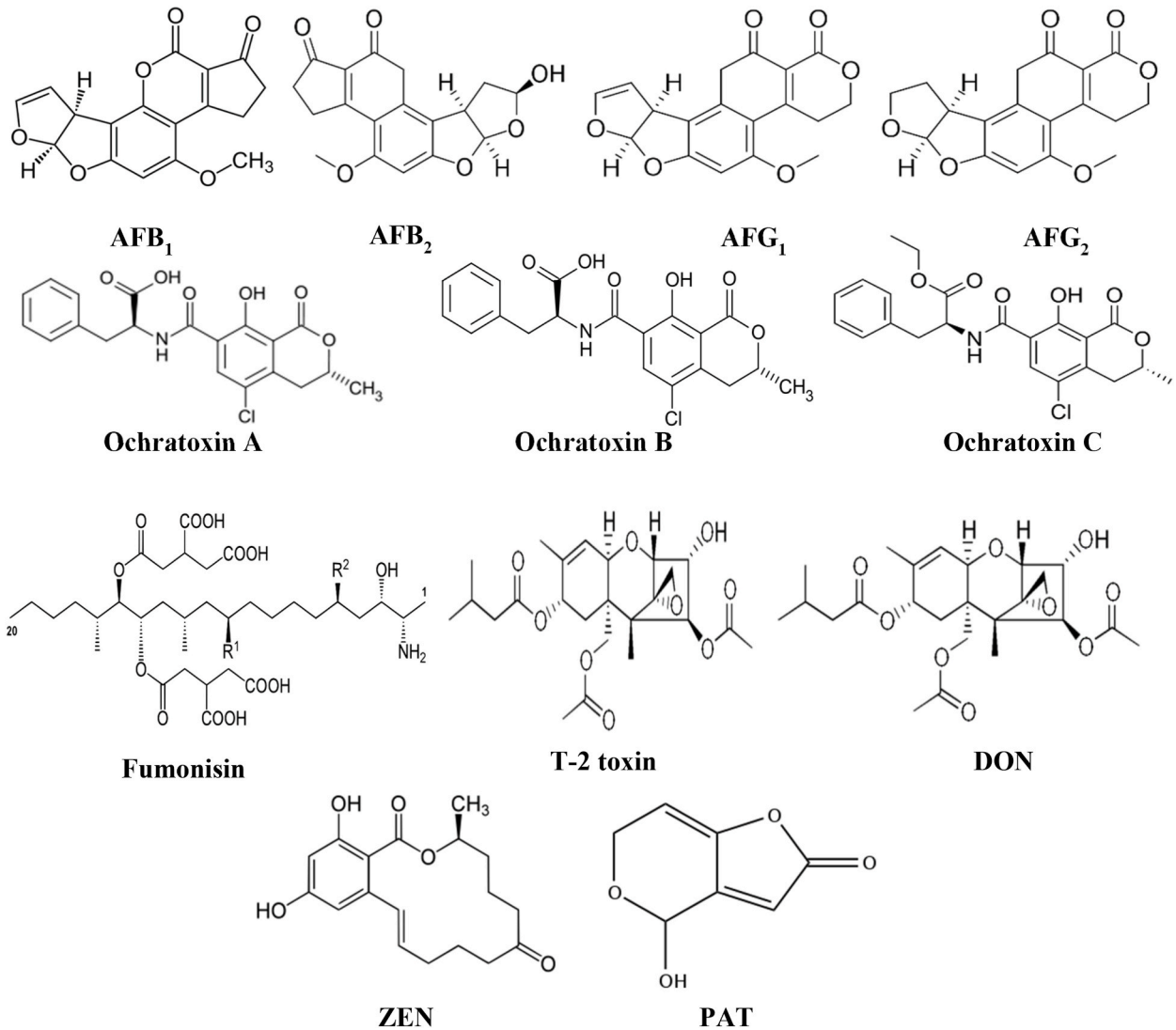

Fig. 1. Chemical structure of major mycotoxins.

control and reduce fungal growth and mycotoxin contamination in various foods. However, it is important to consider that these techniques often cause changes in food substrates, including taste, texture, and nutritional composition [21].

Moreover, some mycotoxins are stable during food manufacturing, suggesting that traditional heat methods may not effectively reduce mycotoxin levels [22]. Consequently, there is a growing trend towards using non-heat methods to reduce mycotoxin levels in food while improving sensory qualities. Therefore, it is imperative to thoroughly analyze novel strategies to enhance their efficacy in mitigating mycotoxins and ensuring food safety. This paper provides a comprehensive review of scientific research on the toxicity of mycotoxins and examines recent advancements in methods for detecting mycotoxin contamination in various food products. Furthermore, this study explores the potential implications and outcomes of current preventive measures, such as cold atmospheric plasma (CAP) technology, polyphenols and flavonoids, magnetic materials and nanoparticles, and natural essential oils (NEOs).

2. Mycotoxins' toxicity

Mycotoxins, produced by pathogenic fungi, pose a health risk when they contaminate cereal crops, fruits, and vegetables [23]. Around 25 % of global grain products are infected with mycotoxins [24]. The chemical structures of major mycotoxins are depicted in Fig. 1, while their extent of toxicity is given in Table 1.

2.1. Aflatoxins

AFs constitute a group of toxic compounds that have been extensively studied, with approximately twenty known types [25–27]. Among these, AFB_1, AFG_1, AFM_1, and AFRo are of particular importance for human health. These toxins are primarily produced by fungi like *A. flavus*, and *A. parasiticus* in hot and humid environments, commonly found in tropical and subtropical regions. Agricultural commodities like wheat, corn, barley, and peanuts are susceptible to AF contamination, especially under conditions of insect damage, drought stress, and suboptimal storage [28,29]. Stricter regulations in the EU set permissible limits for AFs in food, with a lower threshold (0.1 μg/kg) for infants due to their higher vulnerability [30]. The discovery of AF dates back to the "Turkey X disease" incident in 1969, revealing its association with contaminated peanut meal that caused considerable losses in a poultry farm [31]. AFs are linked to various harmful effects, including hepatotoxicity, immunotoxicity, mutagenicity, carcinogenicity, and teratogenicity [32,33]. Aflatoxicosis, resulting from the consumption of AF-contaminated food or feed, primarily effects the liver due to its important metabolic function [34]. Acute exposure to AFs can cause liver malfunction characterized by hepatocyte necrosis, while prolonged

Table 1
Toxic effects of mycotoxins in various food products.

Mycotoxins	Fungi	Foods	Toxicity	References
Aflatoxins B_1, B_2, G_1, G_2, M_1, and M_2	*A. flavus, A. parasiticus, A. nomius, A. pseudotamarii, A. ochraceoroseus, and A. bombycis*	Cereal grains, legumes, fruits, vegetables, and peanut	Hepatocellular carcinoma, mutagenic and teratogenic effects AFM_1 causing abnormalities in fetal development	[28,53–55]
Ochratoxins (OTA, OTB, and OTC)	*A. ochraceus, A. niger, A. carbonarius, P. nordicum, P. viridicatum, and P. verrucosum*	Cereals, legumes, fruits, vegetables, nuts	OTA exhibits hepatotoxic, neurotoxic, teratogenic, and nephrotoxic properties, causing nephropathy in pigs. OTA is associated with renal failures, interstitial nephropathy, urothelial tumors, and BEN in humans.	[25,45, 56–58]
Fumonisins B_1, B_2, B_3	*F. oxysporum* *F. nyagamai* *F. proliferatum*	Corn, beans, soybeans, sorghum, rice, oats	Inhibiting sphingolipid synthesis Linked to esophageal and liver cancers in people. In monkeys, associated with ELEM. In horses, causing respiratory inflammation	[56,59–63]
Trichothecenes e.g., DON, T-2/HT-2 toxins	*F. graminearum* *F. culmorum* *F. poae, F. langsethiae,* *F. sporotrichoides* *Trichoderma* *Stachybotrys* *Trichothecium*	Corn, wheat, barley, and animal-based foods like eggs, kidney, and milk	T-2 toxins and DON permeate cellular membranes, hindering the translation process by interacting with ribosomes. T-2 toxins exposures cause ATA in humans. It also hinders the production of DNA, RNA, and proteins, causing apoptosis, lipid peroxidation, and cytokinesis.	[26,64–68]
Zearalenone	*F. cerealis* *F. graminearum* *F. equiseti, F. culmorum, and* *F. vertillioides*	Corn, wheat, oats, barley, rye	ZEN induces liver cancer, tumors in the uterus, and thyroid adenoma in rats. ZEN causes testicular atrophy, retinopathy, nephropathy, and cataracts in rats. ZEN regulates enzyme expression within biosynthetic pathways.	[69–71]
Patulin	*P. expansum* *P. patulum* *P. urticae* *P. crustosum* *P. griseofulvum*	Apples, apple products, cereals, legumes, seeds, fruits, nuts, vegetables	PAT induces carcinogenicity, mutagenicity, teratogenicity, and neurotoxicity effects in humans. PAT exhibits immunotoxic and neurotoxic properties in animals.	[25,72–75]

exposure may lead to chronic degeneration, fibrosis, and cirrhosis [35,36]. AFs can also affect other organs, including the lungs, myocardium, and kidneys. The susceptibility to these effects can vary among animals based on factors, such as age, sex, health condition, and method of dose administration. Among AFs, AFB_1 is particularly potent, classified as a Group 1 human carcinogen, associated with liver and lung cancer [37]. AFB_1 exposure primarily occurs through diet intake, and its metabolism involves the formation of reactive intermediates like AFB_1 8,9-epoxide (AFBO). AFBO can induce oxidative stress, bind to DNA and proteins, and contribute to hepatocarcinoma development by causing mutations in genes such as the p53 tumor suppressor gene [38]. AFB_1 and its metabolites are excreted via urine and feces [39].

The health effects of AFB_1 exposure range from oxidative stress, DNA damage, and severe liver damage, to symptoms like abdominal pain, diarrhea, jaundice, anorexia, and even death [40]. Acute aflatoxicosis incidents, like the one in Kenya, have resulted in 150 deaths from 2004 to 2005 [41]. On the other hand, chronic exposure to low doses of AFB_1 is associated with hepatocarcinoma, immunosuppression and teratogenicity, stunted growth, and lower birth rates [42,43]. Additionally, AFB_1 exposure is a risk factor for enteropathies and rickets in children.

2.2. Ochratoxin A

OTAs are mycotoxins produced by *Aspergillus* molds, including *A. ochraeus*, *A. niger*, *A. alliaceus*, and *A. glaucus* [44]. These molds contaminate cereals, canned meat, cheese, grapes, coffee, cocoa, and their byproducts (Table 1), particularly in tropical and subtropical regions [45]. OTA is associated with various detrimental effects, including nephrotoxicity, mutagenicity, carcinogenicity, immunotoxicity, teratogenicity, and neurotoxicity [46,47]. It causes ochratoxicosis in humans and animals by disrupting various biological processes, including protein production, lipid peroxidation, calcium metabolism, mitochondrial respiration, and sugar metabolism [48,49]. Experimental data suggests that OTA can pose nephrotoxicity risks to pigs, rats, and chickens. OTA is primarily absorbed in the gastrointestinal tract, with a maximum absorption of 85 % in humans [50]. OTA binds to plasma albumin and is metabolized into OTAα before being eliminated through urine and feces [51]. The mode of action of OTA's carcinogenicity is debated, as animal studies have shown it has both nephrotoxic and carcinogenic effects [52]. Moreover, the genotoxicity of OTA is controversial, with some studies suggesting it indirectly causes DNA damage via oxidative stress.

2.3. Fumonisins

FMNs are mycotoxins predominantly produced by *Fusarium* species, specifically *F. moniliforme*, *F. verticilioides*, and *F. oxysporum* [59,60]. The main types of FMNs are fumonisin B_1 (FB_1) and fumonisin B_2 (FB_2), primarily found in corn and grapes, with FB_1 being a major contaminant in cereals (Fig. 1). FMNs are highly toxic to livestock, causing fatalities in cattle, horses, and rats. In rates, they negatively affect the liver, lungs, and kidneys, while in horses, their exposure can lead to equine leukoencephalomalacia (ELEM), a fatal neurological disease characterized by various symptoms [76]. FMNs are also linked to pulmonary inflammation in swine, and liver cancer in rodents [62]. The IARC categorizes FB_1 and FB_2 as potential carcinogens (Group 2B), suggesting their potential involvement in the development of human tumors [77]. FB_1 competes with ceramide synthases, disrupting cellular processes, and leading to cell damage and apoptosis [78,79]. Recent studies in mice indicate the involvement of nuclear receptors LXR α and β in FB_1 toxicity, effecting cholesterol metabolism [80]. Moreover, FB_1 exposure in animals causes hepatotoxic, nephrotoxic, immunotoxic, and carcinogenic effects [81]. Symptoms like bronchial inflammation and cardiac dysfunction in swine and neural tube and utero developmental defects in mice have also been documented [82]. Besides, the consumption of FB_1 and FB_2 correlates with an increased risk of throat cancer in humans, leading to their classification as group 2B human carcinogen by the IARC [48].

2.4. Trichothecenes

Trichothecenes are cyclic sesquiterpenes synthesized by various fungi, including *Fusarium*, *Trichothecia*, and *Stachybotrys* [59,65]. They are classified into four types, including A, B, C, and D (Fig. 1). Type A trichothecenes are typically found in cereals, such as oats, corn, barley, and oats. Trichothecenes hinder protein synthesis, resulting in membrane dysfunction, cell death, and immune system suppression [83,84]. T-2/HT-2 toxins damage the gastrointestinal tract and skin epithelium, leading to symptoms like nausea, vomiting, and diarrhea. Chronic exposure to such toxins increases susceptibility to infections due to their immunosuppressive effect. T-2 toxin, when converted into HT-2 toxin, has immunological and hematological effects on pigs [85]. The TDI for T-2/HT-2 toxins is 100 ng/kg bw/day for humans. Consuming bread contaminated with T-2 toxin can cause alimentary toxic aleukia (ATA), characterized by severe symptoms, such as necrotic angina, hemorrhaging rash, nosebleeds, fever, nausea, diarrhea, convulsions, and even death [86]. Similarly, T-2 toxin penetrates the skin, causing redness, blisters, burns, and necrosis. Inhaling aerosolized T-2 toxins can damage the respiratory, eyes, and digestive tract [87,88]. Conversely, DON, a mycotoxin classified as Group 3, is non-carcinogenic for humans but induces harmful effects on the upper intestine after being absorbed [89]. DON targets ribosomes, inducing ribotoxic stress, inflammatory responses, and apoptosis [90]. Acute exposure to DON causes vomiting and anorexia while chronic exposure is linked to intestinal lesions, inflammation, and immune modulation. Similarly, chronic exposure to DON worsens inflammation, influencing gastrointestinal epithelial cells and immune responses [91–93].

2.5. Zearalenone

ZEN is a type of mycotoxin produced by *Fusarium* fungi that contaminates wheat, rice, corn, and oats (Fig. 1). ZEN is predominantly

produced by *F. moniliforme*, *F. verticillioides, F. oxysporum*, and *F. equiseti*. ZEN primarily contaminates cereals, chocolate, and some fruits (Table 1). ZEN is primarily absorbed by the proximal intestinal tract and undergoes metabolism, with some metabolites being up to 60 times more potent than the parent molecule [94]. ZEN binds to estrogen receptors, causing a hyperestrogenic effect and disrupting endocrine systems [95]. Elevated levels of ZEN induce toxicity, leading to oxidative stress, and cytotoxicity. The toxicity of ZEN depends on the reactivity of the target organ to estrogens and exposure conditions [96]. Research on pigs as a model population shows that ZEN effects reproductive systems, leading to hyperplasia of the reproductive tract, infertility, and hormonal dysfunctions. Human exposure to ZEN is linked to the development of breast cancer and endometrial hyperplasia. Furthermore, ZEN is hazardous to various organs, including the liver, kidneys, immune cells, and intestines [97,98].

2.6. Patulin

PAT is a mycotoxin synthesized by *P. expansum*, *P. crustosum*, *P. patulum*, and *A. clavatus* (Fig. 1). It frequently contaminates apples, and apple-derived products [73]. Regulatory authorities have set a threshold of 10 μg/L for PAT in fruit drinks [99]. PAT exposure varies among individuals, with adults having an average exposure range of 0.63–21.2 ng/kg body weight/day [100]. The maximum levels of PAT in fruit juices are 50 μg/kg for adults and 10 μg/kg for infants and children's products. PAT is categorized as Group 3, indicating its non-carcinogenic activities in humans. Animal studies show that 50 % of PAT is absorbed in the stomach, metabolized in the liver or kidneys, and excreted via urine [101]. PAT's toxic effects are characterized by synthesizing covalent bonds with sulfhydryl substances, resulting in oxidative stress, apoptosis, and reduced cell viability [102,103]. High doses of PAT can cause acute toxicity, including renal damage, pulmonary congestion, ulcerations, convulsions, edema, and gastrointestinal inflammation [104].

PAT exposure in animals is linked to weight loss, reduced food intake, increased mortality rates, and skeletal malformations in mice [75]. The carcinogenic classification of PAT is currently under review due to insufficient data [105]. Hence, additional research is required to examine its toxicity and potential risks. Understanding the mycotoxin's toxicological profiles and their reliable detection is crucial for assessing the health risks and implementing some suitable prevention and mitigation strategies. Selecting a detection method relies on the target mycotoxin, sample nature, sensitivity, specificity, and availability of the technique. Regular monitoring and testing of mycotoxins are essential to ensure the safety of food products and protect the health of humans and animals.

3. Mycotoxin detection

Compliance with legal regulations on mycotoxins requires implementing proper agricultural practices, adhering to regulated

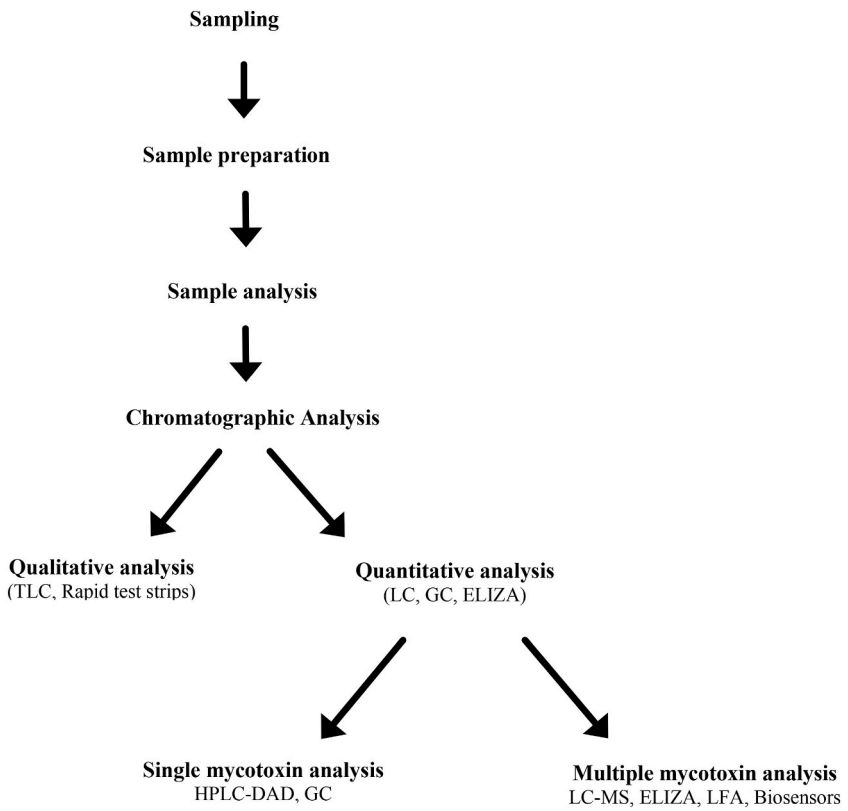

Fig. 2. Flowchart of common steps involved in mycotoxins analysis.

storage conditions, and maintaining clean food processing procedures. Routine product analysis is mandatory due to complex contamination paths. The detection of mycotoxins to ensure their presence within legal limits is crucial due to their toxic nature.

3.1. Sample preparation

Sampling is the initial step in mycotoxin analysis, requiring a representative sample to detect contamination is of key importance. Mycotoxin contamination in samples is not homogenous and can be concentrated in a small area [106,107]. It is crucial to prepare a representative sample using appropriate analytical methods to extract mycotoxins from a matrix. Mycotoxin heterogenic molecular structures (Fig. 1) and different chemical and physical properties (solubility in polar and non-polar solvents) pose a challenge to extracting diverse mycotoxins from a matrix. The water solubilities of DON, ZEN AFB_1, and OTA are 16 μg/mL, 100 μg/mL, 55 mg/mL, and 0.4 μg/mL, signifying the difficulty in extracting mycotoxins simultaneously using water (Fig. 2) [108].

By the end of 2022, around 5500 publications are available on PubMed focused on mycotoxin extraction, discussing strategies for isolating single or multiple toxins. Solvent-based extraction using organic solvents like ethanol, methanol, acetonitrile, or chloroform is frequently employed in the food sector to extract mycotoxins [109–111]. However, using such organic solvents of a toxic nature should be minimized due to their environmental and consumer health risks. Solvent-free methods have also been developed besides the QuEChERS method (Quick, Easy, Cheap, Effective, Rugged, and Safe). Polymers such as polyethylene glycol, detergents, and proteinogenic solubilizers (bovine serum albumin, BSA) can be used for mycotoxins extraction with superheated steam. Such substances are also used in commercial kits like Romer Labs [112,113]. Similarly, naphthyl compounds, specifically naphthalene-1,5-disulfonic acid can extract mycotoxins from samples due to their hydrophobic properties [114]. Sample preparation should produce a solution where the mycotoxins have been fully extracted [115,116]. Sample contamination can be calculated in ng/g by comparing it to the extract contamination in ng/ml extraction buffer [117].

3.1.1. Sample analysis

Mycotoxins can be identified and quantified through various detection methods, including TLC, GC, and HPLC coupled with MS/MS. Currently, immunological techniques, including ELISA or immunoanalytical rapid test methods like test strips (LFA) and biosensors, are becoming popular for the detection of mycotoxins.

3.1.1.1. Chromatographic analysis. TLC is an economical approach for analyzing mycotoxins in different food and feed samples. It involves dissolving the extracted mycotoxins in a solvent and applying it to a silica gel-coated plate [116]. Polar mycotoxins adsorb to the surface, allowing for their separation and detection using UV or fluorescence signals. Due to advancements in chromatographic methods, however, GC and HPLC have replaced TLC due to their improved sensitivity, and better reproducibility [117]. GC is a useful approach for the analysis of volatile organic substances (benzenes and ethanes) but is not fit for mycotoxins due to the low volatility and high polarity of these compounds [118]. Hence, to analyze mycotoxins using GC, their derivatization is necessary to increase volatility, making them suitable for analysis. Coupling GC with mass spectrometry (GC-MS) allows precise detection of mycotoxins after derivatization [119].

Recently, liquid chromatography has become the preferred method due to its ability to handle increased workloads without derivatization or chemical changes. MS or MS/MS efficiently separates mycotoxins based on their mass/charge ratio, allowing them to

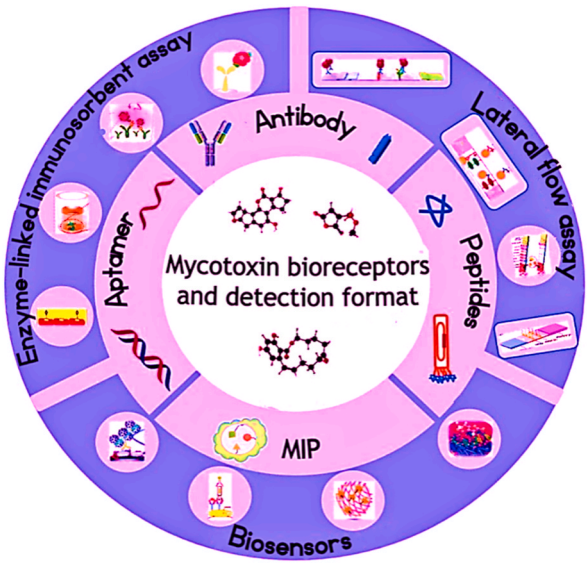

Fig. 3. Schematic illustration of mycotoxins recognition elements and their application.

be detected simultaneously [120]. This method enables the detection of toxins below legal limits by analyzing the peak area measurement signal because of its high sensitivity and reliability [121–123]. However, GC and LC techniques have limitations due to the high cost of the laboratory equipment and expertise required. Due to these limitations, alternative methods like immuno-based assays (ELISA and LFA) have been explored that provide cost-effective, user-friendly, and rapid approaches for mycotoxin detection and quantification.

3.1.1.2. Immuno-based analytics. Immunoanalytical methods like ELISAs and LFAs offer alternatives to chromatographic methods, relying on antibody-antigen binding. ELISA requires substrate conversion for detection, while LFA involves a specific accumulation of gold particles.

3.1.1.3. Enzyme-linked immunosorbent assay. The ELISA is a widely used immuno-based analysis system for mycotoxin determination (Fig. 3) [124–126]. It uses two competitive formats: direct competitive ELISA (dcELISA) and indirect ELISA (icELISA). The dcELISA involves competition between mycotoxin in samples and the analyte-enzyme conjugates for the anti-mycotoxin antibody on the assay plate, while icELISA involves immobilization of analyte-protein conjugates on a microplate. The main antibody targeting anti-mycotoxins can be directly labeled with an enzyme or a secondary antibody-enzyme conjugate to facilitate color development. Horseradish peroxidase (HRP) is commonly used to catalyze the oxidation of tetramethylbenzidine (TMB) oxidation by hydrogen

Table 2
Methods for mycotoxin determination.

Detection Method	Description	Mycotoxins	LOD	Reference
ELISA				
QD-based multiplex assay	Use of CdSe-based QDs with varying sizes	DON, ZEN, AFB_1	3.2 μg/kg, 0.6 μg/kg, 0.2 μg/kg	[131]
Monoclonal Antibodies (MAbs) in ELISA	Use of MAbs in ELISA	AFB_1	0.5–25 ng/mL	[137]
rAb-Based ELISA with Reporter Fusions	rAb-based ELISA with rAb-reporter fusions	AFB_1, OTA, ZEN	0.38 ng/mL, 10 μg/kg, 12 μg/kg	
Nanoluciferase (Nluc) Fusion Assay	Use of Nanoluciferase (Nluc) as a luminescent tracer	Tenuazonic acid	8.60 ng/mL	[147]
Aptamer-Based ELASA	Enzyme-linked aptamer sorbent assay (ELASA)	OTA	1 ng/mL	[134]
Modified Microplate Techniques	Plate coated with antigens or complementary DNA strands in indirect competitive ELISA (icELASA)	OTA, OTB	1 ng/mL, 0.8 ng/mL	[134]
Aptamer Functionalization	Aptamers functionalized with various reporter molecules (e.g., HRP, thrombin, fluorescein)	AFB1, OTA, ATP	10 pM, 20 pM, 20 nM	[135, 137]
Peptide Receptors in dcELISA	Design of a peptide-based dcELISA for OTA detection	OTA	2 μg/L	[138]
Peptide Mimotopes	Epitope-mimicking peptides used as viable alternatives to mycotoxin-protein conjugates in competitive immunoassays dcULISA	ZEN	20 pg/mL	[139]
MIPs Nanoparticle-Based Assay (MINA)	22-fold higher sensitivity than ELISA using mAb.	FB_1	1.9 pM	[146]
LFAs				
PDA-coated gold nanoparticles (AuNPs) LFA	PDA-coated AuNPs-based LFA	ZEN	7.4 pg/mL	[148]
AuNPs and time-resolved fluorescent microspheres-based LFAs	AuNPs and time-resolved fluorescent microspheres (TRFMs) as signal labels	AFB_1, ZEN, DON,	0.59 ng/mL, 0.24 ng/mL, 0.9 ng/mL	[14]
Immunochromatographic strip using anti-idiotypic nanobodies (Aldnb)	Anti-idiotypic nanobodies (Aldnb) as surrogate antigens	AFB_1, ZEN	0.59 ng/mL, 0.24 ng/mL	[149]
Phage-displayed peptide and peptide-MBP fusion	Phage-displayed peptide and peptide-MBP fusion	FB_1, ZEN, OTA	0.25 ng/mL, 3.0 ng/mL, 0.5 ng/mL	[150]
Aptamer-based LFAs		AFB_1, ZEN, OTA	20 ng/mL	[151]
BIOSENSORS				
Impedimetric Immunosensor	Impedimetric immunosensor using OTA-specific pAbs	OTA	0.055 pg/mL	[152]
Chemiluminescence Immunosensor	Chemiluminescence immunosensor using specific mAbs and antigens	AFB_1	2.1 pg/mL	[153]
Impedimetric Immunosensor	Impedimetric immunosensor	OTA	0.055 pg/mL	[152]
Electrochemical Immunosensor	Electrochemical immunosensor for ZEN using Pt-conjugated anti-ZEN mAb	ZEN	0.005 ng/mL	[114]
Photoelectrochemical Immunosensor	Photoelectrochemical immunosensor	AFB_1	1.0 pg/mL	[154]
FRET-Based Immunosensor	Competitive fluorescence resonance energy transfer (FRET)-based immunosensor	OTA	5 pg/mL	[152]
Enzyme-Linked-Immunomagnetic-Electrochemical (ELIME)	ELIME test	DON	100–4500 ng/mL	[155]
Peptide-based electrochemical immunosensor	Peptide-based immunosensor	AFB_1	9.4×10^{-4} μg/L	[156]
Aptasensor with HCR and DNA walkers	Aptasensor	OTA	3.3 fg/mL	[137]
MIP electrochemical Sensor	Electrochemical MIP sensor	PAT	0.66 pM	

peroxide, resulting in a blue color. Alkaline phosphatase (AP) exhibits greater stability and sensitivity than HRP but with a higher cost. Several reporters have been devised to enhance signal amplification alongside enzymes, such as polyHRP, fluorophores, functionalized magnetic beads, and upconverting luminous nanoparticles [127–129].

Glucose oxidase (GOx) has been used as a reporter, converting glucose into gluconic acid and hydrogen peroxide (H_2O_2) using molecular oxygen [130]. HRP catalyzes the conversion of H_2O_2 into hydroxyl radicals, which prompts the aggregation of gold nanoparticles (AuNPs) through tyramine. This led to a significant change in color and dynamic light scattering (DLS) intensity that can be measured using a DLS analyzer [131]. Quantum dots (QDs) with varying sizes exhibit distinct colors, enabling the advancement of a microplate immunoassay to detect several mycotoxins simultaneously. Beloglazova et al. [131] synthesized CdSe-based QDs with varying emission spectra and developed a double-analyte multiplex assay (DAM) that can simultaneously detect AFB_1 and ZEN. Furthermore, various monoclonal antibodies (MAbs) have been designed and utilized in the ELISA to detect AFB_1, OTA, FB_1, T-2/HT-2 toxins, DON, ZEN, PAT, and citrinin (CIT). One major advantage of using recombinant antibody (rAb)-based ELISA is to create rAbs-reporter fusions through genetic engineering, preventing the need for chemical production of antibody-reporter compounds or dependence on commercially available secondary antibodies [132,133].

Aptamers can be used as bioreceptors in microplate assays, specifically enzyme-linked aptamer sorbent assay (ELASA). The immobilization technique used for aptamers on the plate is crucial in preserving their strong binding affinity. A biotinylated aptamer can be immobilized on a streptavidin/avidin surface, and modified microplates are widely used to preserve their binding affinity [134]. The aptamer can be functionalized with various reporter molecules, including HRP, thrombin, and fluorescein, which may reduce detection time and enhance assay sensitivity [135–137].

Several peptide receptors have been engineered and employed as antibody substitutes in mycotoxin analysis using ELISA. Bazin et al. [138] designed a peptide-based dcELISA for detecting OTA via immobilizing the anti-OTA peptide NFO_4 on a microplate. The assay detected OTA at up to 2 μg/L concentrations in wine samples, highlighting its high sensitivity. Epitope-mimicking peptides have also been developed as viable alternatives to mycotoxin-protein conjugates in competitive immunoassays. Analyte-protein conjugates have been used as competitive binders in competitive immunoassays alongside the antibody. However, synthesizing mycotoxin protein conjugates can be challenging due to their complexity, time requirements, and potential risks to humans and the environment. Therefore, phage-displayed peptides, or mimotopes, have been proposed as a potential solution to those limitations [139].

Peptide mimotopes are considered an ideal option as antigen surrogates due to their cost-effectiveness and the ease of genetic engineering involved [140]. Several peptide mimotopes have been discovered and utilized to determine mycotoxin, including AFB_1, ZEN, OTA, FB_1, and DON [141].

Molecularly imprinted polymers (MIPs) have been suggested as substitutes for primary antibodies for developing biomimetic or pseudo ELISAs to detect and quantify mycotoxins. Immobilizing MIPs onto a microplate surface is crucial in establishing a biomimetic ELISA [142,143]. Chianella et al. [144] introduced an innovative approach for immobilization using MIP nanoparticles, similar to the physical adsorption of antibodies in the ELISA [145]. Munawar et al. [146] developed a MIPs nanoparticle-based assay (MINA) to detect FB_1, showing a 22-fold higher sensitivity than an ELISA using monoclonal antibodies (mAb) (Table 2). Comparing antibody-coated microplates to MIP-coated plates, MIP-coated plates offer higher stability, and sensitivity making them suitable for cost-effective storage and transportation at room temperature.

3.1.1.4. Lateral flow assay. LFAs have been widely used in diagnostic tests across various fields, including medicine, veterinary science, and the environment. They allow the analysis of analytes using qualitative and quantitative approaches with shorter detection durations and simpler execution processes compared to microplate-based assays (Fig. 3). Researchers have developed LFAs using polyclonal antibodies (pAbs) and monoclonal antibodies (mAbs) for detecting mycotoxins. The test involves applying a small sample onto a strip, allowing the analytes to pass through the membrane. A test line (T-line) appears after a certain duration, indicating qualitative or semi-quantitative results. The quantification process can also be achieved by utilizing an optical reader. Gold nanoparticles (AuNPs) have been employed as labels in LFA due to their advantages, such as a prominent red color, high stability, simple production, and minimal toxicities [157]. Xu et al. [148] developed polydopamine (PDA)-coated gold nanoparticles (AuNPs) to improve the chromatic intensity and sensitivity of LFA for detecting ZEN in corn. PDA-coated AuNPs showed increased stability, reduced aggregation, and more pronounced color brightness. The assay for mycotoxin detection exhibited a limit of detection (LOD) of 7.4 pg/mL, which was ten times lower than that of AuNP-based LFA [158,159]. Various detecting agents, such as quantum dots (QDs), upconverting nanoparticles (UCNPs), magnetic nanoparticles, and near-infrared (NIR) luminescent colorants, are used in LFA for signal generation [160]. Similarly, various multiplex LFAs have been developed, simultaneously detecting up to six different mycotoxins.

Li et al. [149] developed a TRF LFA utilizing two anti-idiotypic nanobodies (Ald-Nbs) for detecting AFB_1 and ZEN in corn products (Table 2). Their study found that Ald-Nbs effectively retained probes on T-lines for negative specimens, while toxins reacted with the mAb probe in positive samples, reducing capture on T-lines [148]. Yan et al. [150] employed phage display peptide (PDP) and myelin basic peptide (MBP) mixture to create a mimetic antigen, which was then placed onto the T-line. Moreover, aptamer-based LFA has been developed for detecting AFB_1, OTA, and ZEN. Wu et al. [151] devised an LF test strip with aptamers for ZEN detection, relying on competitive binding with the toxin and complementary DNA. Shim et al. [161] constructed a dipstick assay using aptamers to measure AFB_1 levels, which takes 30 min to complete and has a LOD of 0.1 ng/mL when conducted in a buffer solution (Table 2). Aptamers provide superior characteristics and faster test speed than ELIZA, making them useful for monitoring mycotoxin contamination in food processing plants [162].

3.1.1.5. Biosensors. Biosensors are analytical tools that detect and quantify target molecules using biological recognition elements and a signal transducer [163]. They are classified into different types, including immunosensors, aptasensors, peptide-based sensors, and MIPs-based sensors based on bioinspired recognition elements (Fig. 3) [164,165]. They enable real-time monitoring of reactions by generating digital output formats. Mycotoxin screening methods can be enhanced by improving sensitivity, simplicity, robustness, and reusability. Various transducers, including electrochemical, calorimetric, optical, and magnetic, are being investigated for developing mycotoxin sensors [166]. In 2009, Tang and colleagues [127] developed an immunosensor to detect OTA in wines, using pAbs specific for OTA. The electrode immobilizes OTA-BSA, which competes with OTA molecules for binding sites on graphene oxide nanosheets tagged with anti-OTA PAbs. The LOD of the immunosensor was determined to be 0.05 pg/mL, along with an operational range between 0.1 pg/mL and 30 ng/mL (Table 2). Zong et al. [153] devised a chemo luminescence immunosensor to detect AFB_1 and citrinin (CIT), employing mAbs and antigens immobilized on glass slides. Moreover, Lin et al. [167] constructed a novel photoelectrochemical immunoassay for AFB_1, using MnO_2 nanosheets to promote the dissociation of carbon dots. The photocurrent positively correlated with AFB_1 concentration with a 2.1 pg/mL LOD. Moreover, Tang et al. [152] developed a pressure-dependent immunosensor using a microtiter strip to immobilize diacetoxyscirpenol-OVA.

In another study, an anti-M13 bacteriophage antibody coupled with HRP was used to treat a sensor, which was then quantified using voltammetry. This peptide-based immunosensor demonstrated exceptional sensitivity, detecting OTA at concentrations as little as 2.04 fg/mL. In a recent study by Jiang et al. [114], MoS2-thionins were employed to alter a glassy carbon electrode (GCE) following the application of anti-ZEN mAb. Furthermore, Pei et al. [154] devised a photoelectrochemical immunosensor using g-C3N4/Au/WO3 photocatalyst and antibodies, detecting AFB_1 within a concentration ranging between 1.0 ng/mL and 100 ng/mL (Table 2). In 2020, Tang and coworkers [152] constructed a fluorescence resonance energy transfer (FRET)-based immunosensor, utilizing QDs marked with OTA and nanobody. The nanobody-FRET immunosensor showed high sensitivity in detecting OTA, with the capacity to detect quantities as small as 5 pg/mL in 5 min. Romanazzo et al. [155] devised an enzyme-linked-immunomagnetic-electrochemical (ELIME) test to detect DON, utilizing anti-DON Fab fragments with a sensor's functional range of 100–4500 ng/mL. Similarly, Liu et al. [156] used molecular docking and amino acid mutation techniques to generate a peptide library targeting AFB_1. The assays showed a $9.4 \times 10\hat{}-4$ μg/L LOD alongside a linear range between 0.01 μg/L and 20 μg/L for AFB_1. Molecularly imprinted polymers (MIPs) are gaining considerable interest in electrochemical sensor development due to their excellent stability and simplicity [168]. MIP-based electrochemical sensors have already been used to detect AFB_1, FB_1, DON, OTA, and PAT [169]. It is essential to evaluate MIP production and electrode modification methods to optimize MIP-based sensors. Techniques used to produce MIPs include electropolymerization, precipitation polymerization, and bulk polymerization. Electropolymerization is a practical method for generating MIP-based membranes on electrode surfaces, offering quick preparation, easy film thickness regulation, and enhanced cohesion. The photoacoustic technique (PAT) effectively decreased the electrochemical signal, achieving a LOD of 0.66 pM. In conclusion, while various analytical methods such as TLC, GC, HPLC, and MS/MS are relevant, new approaches such as ELISA, LFA, and biosensor-based methods are gaining popularity in the food industry due to their remarkable sensitivity, cost-effectiveness, and portability. However, in addition to developing reliable mycotoxin detection tools, it is important to adopt effective mitigation strategies for mycotoxin contamination.

4. Preventive and control strategies for mycotoxins

Mycotoxin contamination prevent strategies can be pre-harvest or post-harvest measures [19]. Preventive measures during the harvesting process include ensuring timely harvesting, avoiding harvesting with excess moisture, and, if necessary, drying crops before storage [21,32]. Today, the agri-food industry strives for a high standard of quality and safety, using modern technology such as filtration, air sterilization, overpressure sectors, and disinfection of atmospheres and surfaces to produce food under aseptic conditions. Currently, in agriculture, preventing fungal contamination is a challenging task. However, it is essential to avoid superinfection of seeds and fruits through contact with soil and contaminated equipment. Additionally, these contacts cause injuries, which facilitate the penetration of hyphae into the plant. When handling fungal contamination, it is imperative to prevent conidial germination and hyphal development. When mycotoxins are already present in food, it is necessary to implement control strategies to minimize their adverse effects [19,21]. Various decontamination methods can be employed to process food, including physical, chemical, or biological approaches. Most of them can partially destroy or inactivate mycotoxins, but they rarely eliminate them [170].

4.1. Decontamination of food

Decontamination procedures are necessary to reduce mycotoxin contamination in food products [171]. In this context, physical, chemical, and microbiological approaches are applicable. Combining multiple strategies with an integrated approach is often more effective [172]. The Food and Agriculture Organization (FAO) established guidelines for decontamination procedures, such as reducing mycotoxins, preventing toxic residue production, preserving product nutritional and technological attributes, and eliminating spores or mycelial filaments that can produce mycotoxins. Following the given guidelines can effectively reduce the incidence of mycotoxins in foods and feeds, ensuring the safety of both humans and animals.

4.1.1. Conventional approaches

Physical methods, like cooking, baking, and roasting, are often used for food preparation. Some methods, like ozonization or radiation, can help reduce mycotoxin levels in food. However, these methods may not eliminate mycotoxins [173–175]. Chemical compounds, such as hydrogen peroxide, sodium hypochlorite, ascorbic acid, calcium hydroxide, ammonium hydroxide, sulfur dioxide,

and ammonium carbonate, can convert mycotoxins into non-toxic substances. However, these chemicals are unsuitable for food or feed meant for direct consumption [175]. Various additives like vitamin C, bisulfides, curcumin, bentonite, activated carbon, silicate, and glucan-based adsorbents could mitigate the impacts of mycotoxins in infected foods. Similarly, esterified glucomannan has been shown to bind AFs, FMNs, and ZEN simultaneously when added to feed; caution must be exercised as these binders could intensify the harmful effects of certain mycotoxins [173]. Mycotoxins are harmful substances that may contaminate food products. Missiological methods aim to mitigate their toxicity through microbial biodegradation and transformation. For example, the *Flavobacterium aurantiacum* bacterium degrades AFB_1 in milk and meat [173]. Bacteria like *Lactobacillus*, *Bifidobacterium*, *Streptococcus thermophilus*, and *Lactococcus lactis* can bind AFs to their cell walls, rendering them harmless. Additionally, *Kluyveromyces* yeast inhibit *Aspergillus* growth and

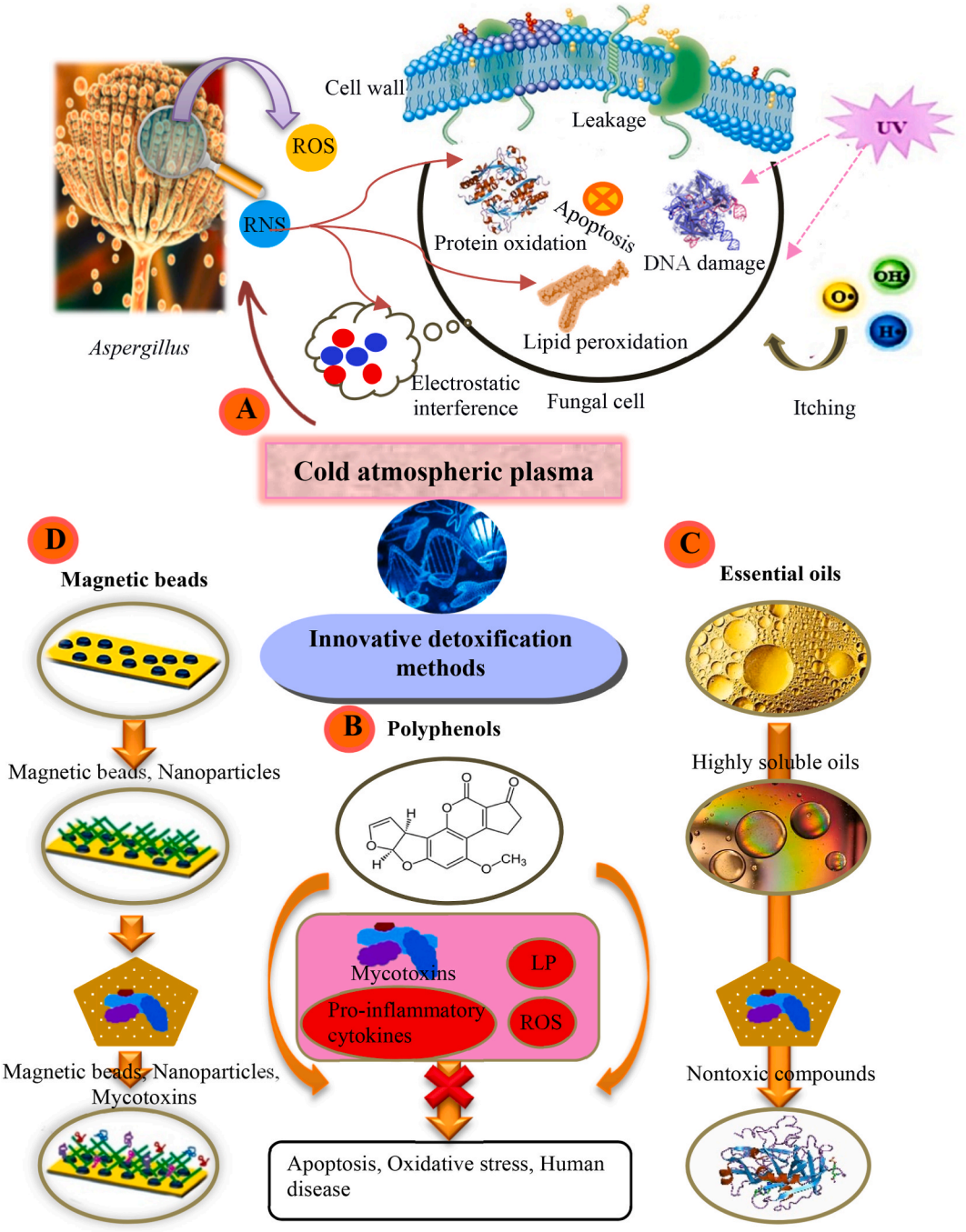

Fig. 4. Methods for controlling mycotoxin contamination: **(A)** cold atmospheric plasma method, **(B)** polyphenols, **(C)** natural essential oils, and **(D)** magnetic materials and nanoparticles.

AF production, suggesting they could help reduce AF contamination [176]. Microbial binders and inhibitors are being investigated for their efficacy in fighting mycotoxin contamination. Naturally occurring macroorganisms show promise in mitigating mycotoxin toxicity in food products, ensuring safety for humans and animals.

4.1.2. Innovative mitigation strategies

Researchers are exploring new strategies to combat mycotoxin toxicity, addressing customer concerns about food hygiene, and improving control measures. These strategies include cold atmospheric plasma (CAP), polyphenols, magnetic materials and nanoparticles, and natural essential oils (NEOs), which aim to mitigate mycotoxin-related health risks without leaving harmful residues on food products (Fig. 4).

4.1.2.1. Cold atmospheric plasma. CAP is a state of matter achieved by subjecting a neutral gas to an electric field, which ionizes certain atoms or molecules within the gas, producing plasma. Reactive oxygen and nitrogen species are produced when the voltage exceeds the breakdown threshold, leading to the formation of CAP at ambient temperature and atmospheric pressure. CAP utilization involves exposing water, buffer solutions, and acids to plasma discharge, which generates sanitizers for washing and disinfection [177, 178]. The system's antimicrobial activity and aptitude to reduce complex biochemical compounds are attributed to a combination of reactive chemistries, including O—2 (superoxide), O_3 (ozone), H_2O_2 (hydrogen peroxide), OH (hydroxyl radicals), ONOO— (peroxynitrite), NO_2— (nitrite), NO—3 (nitrate), ultraviolet (UV) radiation, and a voltage.

These elements collectively maintain a temperature comparable to the ambient levels, giving the nonthermal characteristics of CAP. The efficacy of CAP is influenced by mycotoxin's molecular structure and the conditions under which they are processed. For instance, the effectiveness of degrading DON in wheat-based food is influenced by various factors, including gas type, processing duration, matrix attributes, water, and plasma voltage. Similarly, nitrogen-based CAP produces reactive nitrogen species (RNS) like nitric oxide (NO) and nitrogen dioxide (NO_2), which have antimicrobial properties and are used in food safety, sterilization, and surface disinfection. On the other hand, oxygen-based CAP produces reactive oxygen species (ROS) like ozone (O_3), singlet oxygen (1 O_2), and atomic oxygen (O), which are also used in surface decontamination of mycotoxins. Inert gases like argon or helium serve as carriers for reactive species produced by electrical discharge. Despite its lower reactivity, inert gas-based CAP is still effective in applications such as material surface modification. Therefore, researchers must select an appropriate gas for CAP that aligns with the desired reactive species and specific application requirements, such as antimicrobial treatment.

Chen et al. [97] found that exposing samples to 50 kV atmospheric air plasma for 8 min reduced DON by 25.82 % while increasing water content from 8 % to 20 % enhanced its effectiveness by 36.10 %. Similarly, reducing T-2/HT-2 toxins in oatmeal is affected by factors like relative humidity, time of exposure, and types of gases employed in CAP production. Kiš et al. [179] found that CAP efficiently oxidized samples through nitrogen (N_2), reducing T-2 and HT-2 toxins to 42.24 % and 37.53 %, respectively. Wang et al. [180] discovered that adjusting voltage from 10 to 30 kV reduced alternariol and alternariol monomethyl ether by 1.3 %–56.5 % in jujube juice.

Similarly, corona discharge plasma effectively degrades AFB_1 in rice and wheat samples by 45–56 % after 30 min [181]. This is attributed to the lack of a C8–C9 double bonding in the furofuran rings and modifications in lactone, cyclopentanone, and methoxyl groups caused by oxidative impact from various chemicals. CAP has also been more efficient than gamma irradiation in lowering AFB_1 (70–73 %) and AFB_2 (15–47 %) in hazelnuts, with minimal impact on the sensory properties. Wielogorska et al. [182] found that CAP effectively produces safe products during mycotoxin detoxification. They found that the decrease in AFB_1, OTA, FB_1, DON, ZEN, and enniatin B (ENB) exhibited a first-order kinetic pattern. In their study, ENB and DON had a half-life of 1.1 and 74 min, respectively.

Besides, a 10-min exposure decreased FB_1 and AFB_1 by 64 and 65 %, respectively. The detection of degradation products, specifically AFB_1 and ZEN, was limited and did not affect the cytotoxicity of liver cancer cells. Multiple mechanisms are suggested for the degradation of mycotoxins using CAP, which can be influenced by plasma features like oxygen concentration, hydroxyl radicals, photons, and UV light. Similarly, CAP species function across various spots within fungal cells, leading to structural damage, inactivation, and cellular death. They also degrade toxins via different processes, producing less toxic byproducts [183]. According to Gavahian and Cullen [184] the plasma-produced reactivity may disrupt fungal cellular walls, leading to cytoplasmic discharge and cell deactivation. Lee et al. [185] proposed deactivating *Cordyceps bassiana* spores by altering their structure through plasma-generated reactive species. Later, Wu et al. suggested that CAP detoxifies AFs by disrupting fungal cell walls, cytoplasm, and cell metabolism (Fig. 4A). Overall, plasma-generated reactive compounds can deactivate cells by impacting cell membranes. CAP can enhance cell membrane permeability through oxidation, which damages cell walls. This leads to DNA breakdown, leakage, and degradation of protein molecules in cells. These processes also cause cellular apoptosis and fungal spore contraction [186].

4.1.2.2. Polyphenolic compounds. Polyphenols are garnering attention for their diverse properties including antimicrobial, antiviral, and anti-inflammatory effects [187]. They have different modes of action towards mycotoxins, such as antioxidant properties, lipophilicity, suppression of mycotoxin production-related genes, and inhibition of enzymatic activity linked to mycotoxin synthesis (Fig. 4B). Hamad et al. [188] found that plant-based extracts and polyphenolic compounds possess inhibitory properties against fungal development and can effectively decrease mycotoxins. According to Sanzani et al. [189], umbelliferone and quercetin can decrease gene expression involved in PAT biosynthesis, resulting in decreased accumulation. Likewise, chlorogenic and gallic acids inhibit AFB_1 in beans [190]. Moreover, Salas et al. [191] found that citrus-derived flavanones such as hesperidin and naringin can reduce PAT production by 95 %. Similarly, a β-cyclodextrin-based nanosponge with bioactive phenols can prevent fungal attacks and detoxify mycotoxins [192]. These natural food products have antioxidant and medicinal properties, potentially mitigating mycotoxin-related

harm [193]. Recent studies on polyphenols suggest their potential to mitigate the detrimental effects of fungi and mycotoxins, indicating their promising prospects for future applications.

4.1.2.3. Natural essential oils (NEOs). NEOs are eco-friendly additives that can limit fungi growth and reduce mycotoxin levels in various foods. These additives disrupt essential enzymes in carbohydrate degradation, mycotoxin production (Fig. 4C), and fungal cell structure integrity [194]. They modulate fungal gene expression and interfere with cell membranes through polyphenols, causing damage to cell membranes [195]. Research has shown that NEOs can inhibit mycotoxins.*Origanum majorana* L. essential oil has demonstrated antifungal properties *in vitro* studies, inhibiting the growth of *A. flavus* and AF production. This indicates its ability as an emerging food-preserving agent to enhance food safety [196]. Further research revealed that capsaicin can inhibit OTA production by *A. niger*. Additionally, garlic, rosemary, sage, and mint EOs effectively inhibit OTA production [197]. Similarly, turmeric oil exhibits a strong antifungal effect against *A. flavus*, reducing AF infestation in corn. According to Kedia et al. [198], *Mentha spicata* essential oils effectively inhibited mycotoxins produced by *A. flavus* in chickpeas by targeting the plasma membrane. On the other hand, EOs from lemon, grapefruit, and eucalyptus effectively inhibit ZEN production. Similarly, recent studies showed that EOs from *Curcuma longa* effectively inhibited *Fusarium graminearum* growth and ZEN production [199]. While NEOs show promise in mitigating mycotoxins in food, it is important to be aware of their limitations. For example, the effectiveness of NEOs may be reduced in comparison to synthetic or chemical alternatives and can vary based on the type of mycotoxin and environmental factors. Additionally, the flavors and enticing aromas of these ingredients can affect the overall sensory characteristics of processed foods. The lack of regulations and limitations pose challenges to achieving widespread acceptance, while safety concerns arise due to instability and risk of allergies. The practicality of these products is limited due to concerns regarding their cost, residue, and negative environmental impacts during their production.

4.1.2.4. Magnetic materials and nanoparticles. Recent research has found that magnetic materials and nanoparticles can effectively manage mycotoxin contamination. These techniques are eco-friendly, cost-effective, and efficient in mitigating mycotoxins. Chitosan-coated magnetic particles (Fe_3O_4) have been shown to adsorb PAT from fruit juice efficiently. However, chitosan-coated magnetic

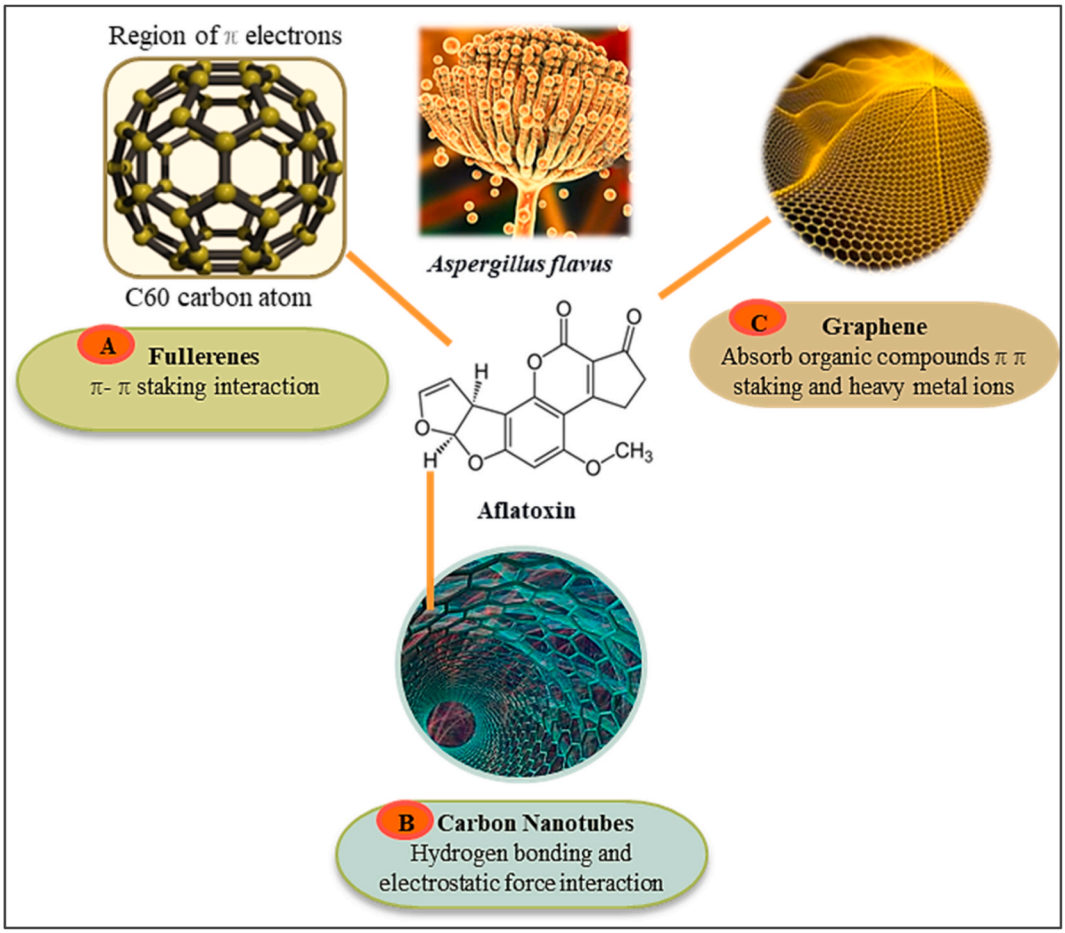

Fig. 5. Mechanism of binding interaction between mycotoxins and nano-scaled adsorbents and, A = fullerenes; B = carbon nanotubes; and C = graphene.

particles could interact with other components in the juice, leading to changes in taste, aroma, color, or texture. This could affect the sensory attributes and overall quality of the juice. Moreover, nano-cellulose and retinoic acid effectively adsorbed AFB_1 from different food sources. These approaches are non-toxic, and effective in optimal pH levels [199]. Various magnetic nanoparticles, including surface-active maghemite (SAMNs), silver nanoparticles (SLN), copper nanoparticles (CN), selenium nanoparticles (SEN), and zinc oxide nanoparticles (ZON), are effective in removing mycotoxins from food products [200]. SEN derived from *Trichoderma harzianum* JF309 has been shown to reduce FB_1 by 63 % and DON by 76 % [201]. SLN inhibits the proliferation of mycotoxin-producing molds, suppressing the synthesis of AF and OTA in corn-based media. Besides, ZON efficiently suppresses the development of *Aspergillus*, *Penicillium,* and *Fusarium* species [202].

Magnetic carbon nanocomposites derived from corn byproducts efficiently remove AFB_1 in poultry, achieving a 90 % removal at pH 7 within 3 h. A mixture of chitosan and glutaraldehyde demonstrated excellent adhesion capacities for various mycotoxins [203]. Nano-fungicides containing phytochemicals like tannins, phloretin, catechols, eugenol, and thymol exhibit optimal antimicrobial properties without posing any risks to humans or animals [204]. Nanoparticle-mediated mycotoxin risk mitigation involves molecular mechanisms like oxidative stress, nucleic acid interactions, and inflammatory responses, which eliminate microbes in plants and mammals (Fig. 4D) [205]. Cell membrane interactions can trigger apoptosis, generate reactive oxygen species, inhibit mitochondrial activities, and facilitate lipid peroxidation or autophagy. For instance, ZON induces ROS production, disrupting fungal cell membranes as observed through scanning electron microscopy (SEM) [206]. Recently, a study suggested that quercetin (Q)-loaded chitosan nanoparticles can induce a hepato-protective cascade, enhancing antioxidant defense mechanisms. This cascade commences with the activation of nuclear factor erythroid 2-related factor 2 (NRF2), leading to heme-oxygenase-1 (HO-1) synthesis. Quercetin inhibits the activity of nitric oxide synthase (NOS) and the production of nitric oxide (NO) induced by lipopolysaccharide through IκB kinase (IKK) and p38 mitogen-activated protein kinases (p38MAPK). The antioxidant response element (ARE) in detoxication promoter genes triggers the transcriptional reaction. The interaction between carbon nanoparticles, including fullerenes, carbon nanotubes, and graphene with mycotoxins has been comprehensively reviewed [205]. However, additional research is necessary to fully comprehend the interaction between nanoparticles and specific components of fungal cells.

4.1.2.5. Other innovative strategies. Pulsed electric fields (PEFs) have emerged as important approaches for preventing *A. flavus* contamination and the synthesis of AFB_1 and AFG_1 [184]. PEFs are efficient in detoxifying mycotoxins in foods. Food-target assessments should be done before implementing PEF methods in food production. Zhang et al. [207] investigated the potential decrease of AFB_1 in corn employing WMTs. The results showed that WMT effectively reduced AFB_1 in corn and prevented heat damage to corn kernels, suggesting the potential of microwave strategies for reducing AFB_1. On the other hand, Gavahian and Cullen [184] explored the use of high-pressure treatment (HPT) to reduce mycotoxins in juices. They also highlighted the potential of active packaging in managing pathogenic molds and mycotoxins in fruits, vegetables, nuts, pastries, and milk products (Fig. 5).

Moreover, biopolymers, including proteins and lipids, are gaining recognition for removing mycotoxins due to their cost-effectiveness, eco-friendliness, and biodegradable nature. Currently, nano-scaled adsorbents, such as calcium and sodium bentonites, are also investigated as food additives to remove OTA from cheese. Hamad et al. [188] assessed the detoxification effectiveness of bentonites in both *in vitro* and *in vivo* settings. Calcium bentonite exhibited better adsorption capacity than sodium bentonite in phosphate-buffered saline (PBS). *In vivo* tests on rats showed similar enzymatic reactions to control samples when OTA and bentonite were present, compared to OTA alone. SEM and Fourier transform infrared spectroscopy (FTIR) confirmed that bentonites are effective OTA binders. Additionally, Ca-bentonite-supplemented feta cheese had enhanced sensory qualities, suggesting its potential as a food-grade adsorbent for separating and eliminating OTA in food products [188]. Fig. 5 depicts the mechanism of binding interaction between mycotoxins and nano-scaled adsorbents.

5. Conclusions and future prospects

Mycotoxins, including AFs, OTA, FMNs, T-2 toxins, ZEN, and PAT, can exhibit a wide range of toxic effects on both humans and animals. AFs, particularly AFB_1, pose hepatotoxic, immunotoxic, and carcinogenic risks, leading to both acute and chronic health complications. OTA specifically targets the kidneys and induces nephrotoxic, mutagenic, carcinogenic, and teratogenic effects, while its genotoxicity remains a subject of debate. FMNs are linked to liver cancer and developmental issues in humans. T-2/HT-2 toxins inhibit protein synthesis, resulting in immunosuppression effects, as well as gastrointestinal, and dermatological complications. ZEN, a non-carcinogenic estrogenic toxin, affects the reproductive systems and various other organs, while PAT induces oxidative stress and acute toxicity. Therefore, it is imperative to regularly monitor foods and feeds and implement preventive measures to effectively mitigate the health risks associated with mycotoxins. While extensive research has been conducted on regulated mycotoxins in food and feed products, emerging mycotoxins lack specific regulations, posing risks to human and animal health. There is still a need for continued research on toxicity, risk assessment, and detection methods for emerging mycotoxins like NX-toxins, and their degradation byproducts such as *cis*-ZEN, and enniatins. In this connection, the development of improved recognition components, analytical methods, and diagnostic kits can play a pivotal role in ensuring food safety amidst the ever-changing mycotoxin challenges.

The mitigation of fungal contamination in foods necessitates the implementation of an integrated approach that involves physical, chemical, and microbiological detoxification methods. Moreover, the emergence of novel fungal strains has prompted scientific research into cutting-edge techniques, such as CAP technology, polyphenolic inhibitors, magnetic materials, nanoparticles, and NEOs. The effectiveness of these methods can be influenced by various internal and external factors, including substrate type, contaminants, water content, chemical components, and processing environments. The utilization of CAP technology presents a viable and

sustainable approach to mitigating mycotoxin contamination in food products. However, it is imperative to exercise caution and adhere to precise application parameters to mitigate the production of related harmful compounds. Further research is required to enhance the effectiveness of CAP, considering variations in mycotoxins, food matrices, and processing. Besides, polyphenolic compounds showed the potential to inhibit mycotoxin production, however, additional research is required to fully comprehend their mechanisms and efficacy. Furthermore, the potential of NEOs demands careful consideration, particularly in response to challenges related to bioavailability, volatility, oxidation susceptibility, and insolubility. Magnetic materials and nanoparticles possess promising potential for the adsorption of mycotoxins. However, additional research is required to ensure their safe and efficient implementation within the food, agriculture, and livestock industries. Continued research and development in these areas, along with a focus on understanding the factors influencing the effectiveness of these methods, are crucial for reducing mycotoxin risks, ensuring food safety, and protecting consumer health.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Rahim Khan: Writing – original draft, Writing – review & editing, Conceptualization. **Farooq Anwar:** Writing – review & editing. **Farinazleen Mohamad Ghazali:** Conceptualization.

Declaration of competing interest

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

Acknowledgments

The authors acknowledged that the manuscript had undergone a thorough review and received unanimous approval, thereby consenting to its submission to the Journal.

References

[1] D. Umereweneza, T. Kamizikunze, T. Muhizi, Assessment of mycotoxins types in some foodstuff consumed in Rwanda, Food Control 85 (2018) 432–436.
[2] S.M. Abd-Elghany, K.I. Sallam, Rapid determination of total aflatoxins and ochratoxins A in meat products by immuno-affinity fluorimetry, Food Chem. 179 (2015) 253–256.
[3] C. Atherstone, D. Grace, F. Waliyar, J. Lindahl, M. Osiru, Aflatoxin Literature Synthesis and Risk Mapping: Special Emphasis on Sub-saharan Africa, 2014.
[4] C. Montanari, E. Bargossi, A. Gardini, R. Lanciotti, R. Magnani, F. Gardini, G. Tabanelli, Correlation between volatile profiles of Italian fermented sausages and their size and starter culture, Food Chem. 192 (2016) 736–744.
[5] J. Pleadin, J. Frece, K. Markov, Mycotoxins in food and feed, Adv. Food Nutr. Res. 89 (2019) 297–345.
[6] I. Rodrigues, K. Naehrer, A three-year survey on the worldwide occurrence of mycotoxins in feedstuffs and feed, Toxins 4 (9) (2012) 663–675.
[7] W.S. Darwish, Y. Ikenaka, S.M. Nakayama, M. Ishizuka, An overview on mycotoxin contamination of foods in Africa, J. Vet. Med. Sci. 76 (6) (2014) 789–797.
[8] Á. Mesterházy, J. Oláh, J. Popp, Losses in the grain supply chain: causes and solutions, Sustainability 12 (6) (2020) 2342.
[9] P. Vila-Donat, S. Marín, V. Sanchis, A.J. Ramos, A review of the mycotoxin adsorbing agents, with an emphasis on their multi-binding capacity, for animal feed decontamination, Food Chem. Toxicol. 114 (2018) 246–259.
[10] G.S. Shephard, Impact of mycotoxins on human health in developing countries, Food Addit. Contam. 25 (2) (2008) 146–151.
[11] L. Anfossi, C. Giovannoli, C. Baggiani, Mycotoxin detection, Curr. Opin. Biotechnol. 37 (2016) 120–126.
[12] A. Alshannaq, J.H. Yu, Occurrence, toxicity, and analysis of major mycotoxins in food, Int. J. Environ. Res. Publ. Health 14 (6) (2017) 632.
[13] C.J. Amuzie, J.J. Pestka, Suppression of insulin-like growth factor acid-labile subunit expression—a novel mechanism for deoxynivalenol-induced growth retardation, Toxicol. Sci. 113 (2) (2010) 412–421.
[14] D. Liu, L. Ge, Q. Wang, J. Su, X. Chen, C. Wang, K. Huang, Low-level contamination of deoxynivalenol: a threat from environmental toxins to porcine epidemic diarrhea virus infection, Environ. Int. 143 (2020) 105949.
[15] E. Song, X. Xia, C. Su, W. Dong, Y. Xian, W. Wang, Y. Song, Hepatotoxicity and genotoxicity of patulin in mice, and its modulation by green tea polyphenols administration, Food Chem. Toxicol. 71 (2014) 122–127.
[16] D. Rašić, D. Želježić, N. Kopjar, D. Kifer, M.Š. Klarić, M. Peraica, DNA damage in rat kidneys and liver upon subchronic exposure to single and combined ochratoxin A and citrinin, World Mycotoxin J. 12 (2) (2019) 163–172.
[17] H. Zhou, S. George, C. Hay, J. Lee, H. Qian, X. Sun, Individual and combined effects of aflatoxin B_1, deoxynivalenol and zearalenone on HepG2 and RAW 264.7 cell lines, Food Chem. Toxicol. 103 (2017) 18–27.
[18] L.H. Sun, M.Y. Lei, N.Y. Zhang, X. Gao, C. Li, C.S. Krumm, D.S. Qi, Individual and combined cytotoxic effects of aflatoxin B_1, zearalenone, deoxynivalenol and fumonisin B_1 on BRL 3A rat liver cells, Toxicon 95 (2015) 6–12.
[19] C.G. Awuchi, E.N. Ondari, I.J. Eseoghene, H. Twinomuhwezi, I.O. Amagwula, S. Morya, Fungal growth and mycotoxins production: types, toxicities, control strategies, and detoxification, Fungal Reproduction and Growth (2021) 100207.
[20] R.A. Marc, Implications of mycotoxins in food safety, in: Mycotoxins and Food Safety-Recent Advances, IntechOpen, 2022.
[21] Z.H. Zhang, L.H. Wang, X.A. Zeng, Z. Han, C.S. Brennan, Non-thermal technologies and its current and future application in the food industry: a review, Int. J. Food Sci. Technol. 54 (1) (2019) 1–13.
[22] W.X. Peng, J.L.M. Marchal, A.F.B. Van der Poel, Strategies to prevent and reduce mycotoxins for compound feed manufacturing, Anim. Feed Sci. Technol. 237 (2018) 129–153.
[23] E.M. Binder, Managing the risk of mycotoxins in modern feed production, Anim. Feed Sci. Technol. 133 (1–2) (2007) 149–166.
[24] E. Streit, C. Schwab, M. Sulyok, K. Naehrer, R. Krska, G. Schatzmayr, Multi-mycotoxin screening reveals the occurrence of 139 different secondary metabolites in feed and feed ingredients, Toxins 5 (3) (2013) 504–523.

[25] F. Malíř, V. Ostrý, Vláknité Mikromycety (Plísně), Mykotoxiny a Zdraví Člověka [Filamentous Micromycetes (Molds), Mycotoxins and Human Health], vol. 349, 2003. Brno. [in Czech].
[26] J. Patocka, Bolesatine, a toxic protein from the mushroom *Rubroboletus satanas*, Military Medical Science Letters 87 (1) (2018) 14–20.
[27] V. Ostry, F. Malir, J. Toman, Y. Grosse, Mycotoxins as human carcinogens—the IARC Monographs classification, Mycotoxin Res. 33 (2017) 65–73.
[28] J.C. Frisvad, V. Hubka, C.N. Ezekiel, S.B. Hong, A. Novßkovß, A.J. Chen, J. Houbraken, Taxonomy of *Aspergillus* section *Flavi* and their production of aflatoxins, ochratoxins, and other mycotoxins, Stud. Mycol. 93 (1) (2019) 1–63.
[29] R. Khan, F.M. Ghazali, N.A. Mahyudin, N.I.P. Samsudin, Aflatoxin biosynthesis, genetic regulation, toxicity, and control strategies: a review, Journal of Fungi 7 (8) (2021) 606.
[30] R.S. Chhaya, J. O'Brien, E. Cummins, Feed to fork risk assessment of mycotoxins under climate change influences-recent developments, Trends Food Sci. Technol. 126 (2022) 126–141.
[31] M. Harčárová, E. Čonková, Z. Sihelská, Mycobiota and mycotoxic contamination of feed cereals, Folia Vet. 62 (4) (2018) 5–11.
[32] P. Kumar, D.K. Mahato, M. Kamle, T.K. Mohanta, S.G. Kang, Aflatoxins: a global concern for food safety, human health, and their management, Front. Microbiol. 7 (2017) 2170.
[33] D.L. Eaton, J.D. Groopman, The Toxicology of Aflatoxins: Human Health, Veterinary, and Agricultural Significance, Elsevier, 2013.
[34] S. Amaike, N.P. Keller, Aspergillus flavus, Annu. Rev. Phytopathol. 49 (2011) 107–133.
[35] Y.Y. Gong, S. Watson, M.N. Routledge, Aflatoxin exposure and associated human health effects, a review of epidemiological studies, Food Safety 4 (1) (2016) 14–27.
[36] R. Khan, F.M. Ghazali, N.A. Mahyudin, N.I.P. Samsudin, Morphological characterization and determination of aflatoxigenic and non-aflatoxigenic *Aspergillus flavus* isolated from sweet corn kernels and soil in Malaysia, Agriculture 10 (10) (2020) 450.
[37] J. Bennett, S. Kale, J. Yu, Aflatoxins: background, toxicology, and molecular biology, in: Foodborne Diseases, Springer, 2007, pp. 355–373.
[38] R. Khan, F.M. Ghazali, N.A. Mahyudin, N.I.P. Samsudin, Biocontrol of aflatoxins using non-aflatoxigenic *Aspergillus flavus*: a literature review, Journal of Fungi 7 (5) (2021) 381.
[39] P.A. Egner, X. Yu, J.K. Johnson, C.K. Nathasingh, J.D. Groopman, T.W. Kensler, B.D. Roebuck, Identification of aflatoxin M1-N7-guanine in liver and urine of tree shrews and rats following administration of aflatoxin B_1, Chem. Res. Toxicol. 16 (9) (2003) 1174–1180.
[40] E.O. Da Silva, A.P.F.L. Bracarense, I.P. Oswald, Mycotoxins and oxidative stress: where are we? World Mycotoxin J. 11 (1) (2018) 113–134.
[41] M.N. Okioma, The 2004 and 2005 aflatoxin tragedies in Kenya-a case study, in: Mycotoxins: Detection Methods, Management, Public Health, and Agricultural Trade, CABI, Wallingford UK, 2008, pp. 127–131.
[42] S. Marchese, A. Polo, A. Ariano, S. Velotto, S. Costantini, L. Severino, Aflatoxin B_1 and M_1: biological properties and their involvement in cancer development, Toxins 10 (6) (2018) 214.
[43] H.L. Meiselman, S.R. Jaeger, B.T. Carr, A. Churchill, Approaching 100 years of sensory and consumer science: developments and ongoing issues, Food Qual. Prefer. 100 (2022) 104614.
[44] F. Malir, V. Ostry, A. Pfohl-Leszkowicz, J. Malir, J. Toman, Ochratoxin A: 50 years of research, Toxins 8 (7) (2016) 191.
[45] A.A. Ismaiel, J. Papenbrock, Mycotoxins: producing fungi and mechanisms of phytotoxicity, Agriculture 5 (3) (2015) 492–537.
[46] M.E.B. da Rocha, F.D.C.O. Freire, F.E.F. Maia, M.I.F. Guedes, D. Rondina, Mycotoxins and their effects on human and animal health, Food Control 36 (1) (2014) 159–165.
[47] A. Pfohl-Leszkowicz, R.A. Manderville, Ochratoxin A: an overview on toxicity and carcinogenicity in animals and humans, Mol. Nutr. Food Res. 51 (1) (2007) 61–99.
[48] L. Claeys, C. Romano, K. De Ruyck, H. Wilson, B. Fervers, M. Korenjak, I. Huybrechts, Mycotoxin exposure and human cancer risk: a systematic review of epidemiological studies, Compr. Rev. Food Sci. Food Saf. 19 (4) (2020) 1449–1464.
[49] T. Kőszegi, M. Poór, Ochratoxin A: molecular interactions, mechanisms of toxicity and prevention at the molecular level, Toxins 8 (4) (2016) 111.
[50] D. Dietrich, A.H. Heussner, E. O'Brien, Ochratoxin A: comparative pharmacokinetics and toxicological implications (experimental and domestic animals and humans), Food Addit. Contam. 22 (s1) (2005) 45–52.
[51] M. Zingerle, S. Silbernagl, M. Gekle, Reabsorption of the nephrotoxin ochratoxin A along the rat nephron *in vivo*, J. Pharmacol. Exp. Therapeut. 280 (1) (1997) 220–224.
[52] A.H. Heussner, L.E. Bingle, Comparative ochratoxin toxicity: a review of the available data, Toxins 7 (10) (2015) 4253–4282.
[53] F. Chu, I. Ueno, Production of antibody against aflatoxin B_1, Appl. Environ. Microbiol. 33 (5) (1977) 1125–1128.
[54] R.A. El-Sayed, A.B. Jebur, W. Kang, F.M. El-Demerdash, An overview on the major mycotoxins in food products: characteristics, toxicity, and analysis, Journal of Future Foods 2 (2) (2022) 91–102.
[55] J.L. Richard, Some major mycotoxins and their mycotoxicoses—an overview, Int. J. Food Microbiol. 119 (1–2) (2007) 3–10.
[56] Y. Tao, S. Xie, F. Xu, A. Liu, Y. Wang, D. Chen, Z. Yuan, A. Ochratoxin, Toxicity, oxidative stress, and metabolism, Food Chem. Toxicol. 112 (2018) 320–331.
[57] L. Pinotti, M. Ottoboni, C. Giromini, V. Dell'Orto, F. Cheli, Mycotoxin contamination in the EU feed supply chain: a focus on cereal byproducts, Toxins 8 (2) (2016) 45.
[58] P. Bayman, J.L. Baker, M.A. Doster, T.J. Michailides, N.E. Mahoney, Ochratoxin production by the *Aspergillus ochraceus* group and *Aspergillus alliaceus*, Appl. Environ. Microbiol. 68 (5) (2002) 2326–2329.
[59] S. Marin, A.J. Ramos, G. Cano-Sancho, V. Sanchis, Mycotoxins: occurrence, toxicology, and exposure assessment, Food Chem. Toxicol. 60 (2013) 218–237.
[60] M. Kamle, D.K. Mahato, S. Devi, K.E. Lee, S.G. Kang, P. Kumar, Fumonisins: impact on agriculture, food, and human health and their management strategies, Toxins 11 (6) (2019) 328.
[61] S.A. Adeyeye, Fungal mycotoxins in foods: a review, Cogent Food Agric. 2 (1) (2016) 1213127.
[62] W.C.A. Gelderblom, W.F.O. Marasas, Controversies in fumonisin mycotoxicology and risk assessment, Hum. Exp. Toxicol. 31 (3) (2012) 215–235.
[63] M. Landoni, D. Puglisi, E. Cassani, G. Borlini, G. Brunoldi, C. Comaschi, R. Pilu, Phlobaphenes modify pericarp thickness in maize and accumulation of the fumonisin mycotoxins, Sci. Rep. 10 (1) (2020) 1417.
[64] A.V. Nathanail, E. Varga, J. Meng-Reiterer, C. Bueschl, H. Michlmayr, A. Malachova, F. Berthiller, Metabolism of the *Fusarium* mycotoxins T-2 toxin and HT-2 toxin in wheat, J. Agric. Food Chem. 63 (35) (2015) 7862–7872.
[65] R. Bhat, R.V. Rai, A.A. Karim, Mycotoxins in food and feed: present status and future concerns, Compr. Rev. Food Sci. Food Saf. 9 (1) (2010) 57–81.
[66] N.A. Foroud, D. Baines, T.Y. Gagkaeva, N. Thakor, A. Badea, B. Steiner, H. Bürstmayr, Trichothecenes in cereal grains–an update, Toxins 11 (11) (2019) 634.
[67] Council for Agricultural, Mycotoxins: Risks in Plant, Animal, and Human Systems: Council for Agricultural, 2003.
[68] V. Klaban, Microscopic World and the phenomenon of symbiosis in the natural environment, Micro: The Foundation Stone of the Biosphere (2021) 243–261.
[69] E. Čonková, A. Laciakova, G. Kováč, H. Seidel, Fusarial toxins and their role in animal diseases, Vet. J. 165 (3) (2003) 214–220.
[70] V. Ostry, F. Malir, J. Toman, Y. Grosse, Mycotoxins as human carcinogens-the IARC Monographs classification, Mycotoxin Res. 33 (1) (2017) 65–73.
[71] M. Mazaheri, M.M. Maymand, A. Gilasgar, A. Akbarzadeh, M.H. Manafi, Quantification of the zearalenone in maize oil with no clean-up, Food Control 127 (2021) 108166.
[72] M. de Champdore, P. Bazzicalupo, L. De Napoli, D. Montesarchio, G. Di Fabio, I. Cocozza, S. D'Auria, A new competitive fluorescence assay for the detection of patulin toxin, Anal. Chem. 79 (2) (2007) 751–757.
[73] M.S. Tapia, S.M. Alzamora, J. Chirife, Effects of water activity (aw) on microbial stability as a hurdle in food preservation, Water activity in foods: Fundamentals and Applications (2020) 323–355.
[74] M.A. Gomes, D.G. Priolli, J.G. Tralhao, M.F. Botelho, Hepatocellular carcinoma: epidemiology, biology, diagnosis, and therapies, Rev. Assoc. Med. Bras. 59 (5) (2013) 514–524.
[75] J.C. Frisvad, L.L. Møller, T.O. Larsen, R. Kumar, J. Arnau, Safety of the fungal workhorses of industrial biotechnology: update on the mycotoxin and secondary metabolite potential of *Aspergillus niger, Aspergillus oryzae*, and *Trichoderma reesei*, Appl. Microbiol. Biotechnol. 102 (2018) 9481–9515.

[76] D.P. Morgavi, R.T. Riley, An historical overview of field disease outbreaks known or suspected to be caused by consumption of feeds contaminated with *Fusarium* toxins, Anim. Feed Sci. Technol. 137 (3–4) (2007) 201–212.
[77] K. De Ruyck, M. De Boevre, I. Huybrechts, S. De Saeger, Dietary mycotoxins, co-exposure, and carcinogenesis in humans: short review, Mutat. Res. Rev. Mutat. Res. 766 (2015) 32–41.
[78] S. Bouhet, E. Hourcade, N. Loiseau, A. Fikry, S. Martinez, M. Roselli, I.P. Oswald, The mycotoxin fumonisin B_1 alters the proliferation and the barrier function of porcine intestinal epithelial cells, Toxicol. Sci. 77 (1) (2004) 165–171.
[79] R.T. Riley, A.H. Merrill, Ceramide synthase inhibition by fumonisins: a perfect storm of perturbed sphingolipid metabolism, signaling, and disease [S], JLR (J. Lipid Res.) 60 (7) (2019) 1183–1189.
[80] M. Régnier, P. Gourbeyre, P. Pinton, S. Napper, J. Laffite, A.M. Cossalter, I.P. Oswald, Identification of signaling pathways targeted by the food contaminant FB_1: transcriptome and kinome analysis of samples from pig liver and intestine, Mol. Nutr. Food Res. 61 (12) (2017) 1700433.
[81] S. Bouhet, I.P. Oswald, The intestine as a possible target for fumonisin toxicity, Mol. Nutr. Food Res. 51 (8) (2007) 925–931.
[82] W.M. Haschek-Hock, C.G. Rousseaux, M.A. Wallig, B. Bolon, Haschek and Rousseaux's handbook of toxicologic pathology, in: Principles and Practice of Toxicologic Pathology, ume 1, Academic Press, 2021.
[83] S.P. McCormick, A.M. Stanley, N.A. Stover, N.J. Alexander, Trichothecenes: from simple to complex mycotoxins, Toxins 3 (7) (2011) 802–814.
[84] F. Fung, R.F. Clark, Health effects of mycotoxins: a toxicological overview, J. Toxicol. Clin. Toxicol. 42 (2) (2004) 217–234.
[85] H. Fromme, M. Gareis, W. Völkel, C. Gottschalk, Overall internal exposure to mycotoxins and their occurrence in occupational and residential settings–An overview, Int. J. Hyg Environ. Health 219 (2) (2016) 143–165.
[86] E. Wambacq, I. Vanhoutte, K. Audenaert, L. De Gelder, G. Haesaert, Occurrence, prevention and remediation of toxigenic fungi and mycotoxins in silage: a review, J. Sci. Food Agric. 96 (7) (2016) 2284–2302.
[87] P.D. Anderson, Bioterrorism: toxins as weapons, J. Pharm. Pract. 25 (2) (2012) 121–129.
[88] B.G. Dorner, R. Zeleny, K. Harju, J.A. Hennekinne, P. Vanninen, H. Schimmel, A. Rummel, Biological toxins of potential bioterrorism risk: current status of detection and identification technology, TrAC, Trends Anal. Chem. 85 (2016) 89–102.
[89] W. Schelstraete, M. Devreese, S. Croubels, Comparative toxicokinetics of *Fusarium* mycotoxins in pigs and humans, Food Chem. Toxicol. 137 (2020) 111140.
[90] D. Payros, I. Alassane-Kpembi, A. Pierron, N. Loiseau, P. Pinton, I.P. Oswald, Toxicology of deoxynivalenol and its acetylated and modified forms, Arch. Toxicol. 90 (2016) 2931–2957.
[91] M. Maresca, N. Yahi, L. Younès-Sakr, M. Boyron, B. Caporiccio, J. Fantini, Both direct and indirect effects account for the pro-inflammatory activity of enteropathogenic mycotoxins on the human intestinal epithelium: stimulation of interleukin-8 secretion, potentiation of interleukin-1β effect and increase in the transepithelial passage of commensal bacteria, Toxicol. Appl. Pharmacol. 228 (1) (2008) 84–92.
[92] P. Pinton, F. Accensi, E. Beauchamp, A.M. Cossalter, P. Callu, F. Grosjean, I.P. Oswald, Ingestion of deoxynivalenol (DON) contaminated feed alters the pig vaccinal immune responses, Toxicol. Lett. 177 (3) (2008) 215–222.
[93] B. Grenier, T.J. Applegate, Modulation of intestinal functions following mycotoxin ingestion: meta-analysis of published experiments in animals, Toxins 5 (2) (2013) 396–430.
[94] H. Steinkellner, M. Binaglia, C. Dall'Asta, A.C. Gutleb, M. Metzler, I.P. Oswald, J. Alexander, Combined hazard assessment of mycotoxins and their modified forms applying relative potency factors: zearalenone and T2/HT2 toxin, Food Chem. Toxicol. 131 (2019) 110599.
[95] A. Kowalska, K. Walkiewicz, P. Kozieł, M. Muc-Wierzgoń, Aflatoxins: characteristics and impact on human health, Adv. Hyg. Exp. Med. 71 (2017) 315–327.
[96] I. Hennig-Pauka, F.J. Koch, S. Schaumberger, B. Woechtl, J. Novak, M. Sulyok, V. Nagl, Current challenges in the diagnosis of zearalenone toxicosis as illustrated by a field case of hyperestrogenism in suckling piglets, Porcine Health Management 4 (1) (2018) 1–9.
[97] P. Chen, T. Liu, S. Jiang, Z. Yang, L. Huang, F. Liu, Effects of purified zearalenone on selected immunological and histopathologic measurements of spleen in post-weanling gilts, Animal Nutrition 3 (3) (2017) 212–218.
[98] H.S. Schmidt, M. Schulz, C. Focke, S. Becker, B. Cramer, H.U. Humpf, Glucosylation of T-2 and HT-2 toxins using biotransformation and chemical synthesis: preparation, stereochemistry, and stability, Mycotoxin Res. 34 (2018) 159–172.
[99] H.P. Egmond, R.C. Schothorst, M.A. Jonker, Regulations relating to mycotoxins in food, Anal. Bioanal. Chem. 1 (389) (2007) 147–157.
[100] K. Vin, G. Rivière, S. Leconte, J.P. Cravedi, J.M. Fremy, I.P. Oswald, V. Sirot, Dietary exposure to mycotoxins in the French infant total diet study, Food Chem. Toxicol. 140 (2020) 111301.
[101] M. Boussabbeh, I. Ben-Salem, A. Prola, A. Guilbert, H. Bacha, S. Abid-Essefi, C. Lemaire, Patulin induces apoptosis through ROS-mediated endoplasmic reticulum stress pathway, Toxicol. Sci. 144 (2) (2015) 328–337.
[102] J. Tannous, S.P. Snini, R. El Khoury, C. Canlet, P. Pinton, Y. Lippi, O. Puel, Patulin transformation products and last intermediates in its biosynthetic pathway, E-and Z-ascladiol, are not toxic to human cells, Arch. Toxicol. 91 (2017) 2455–2467.
[103] R. Mahfoud, M. Maresca, N. Garmy, J. Fantini, The mycotoxin patulin alters the barrier function of the intestinal epithelium: mechanism of action of the toxin and protective effects of glutathione, Toxicol. Appl. Pharmacol. 181 (3) (2002) 209–218.
[104] S.A. Lewis, J.R. Berg, T.J. Kleine, Modulation of epithelial permeability by extracellular macromolecules, Physiol. Rev. 75 (3) (1995) 561–589.
[105] O. Puel, P. Galtier, I.P. Oswald, Biosynthesis and toxicological effects of patulin, Toxins 2 (4) (2010) 613–631.
[106] W. Ala, Graphene-based Sensor of Aflatoxin Molecule: a Simulation-Based Investigation, 2023. Politecnico di Torino.
[107] F. Cheli, A. Campagnoli, L. Pinotti, E. Fusi, V. Dell'Orto, Sampling feed for mycotoxins: acquiring knowledge from food, Ital. J. Anim. Sci. 8 (1) (2009) 5–22.
[108] P. Karlovsky, M. Suman, F. Berthiller, J. De Meester, G. Eisenbrand, I. Perrin, P. Dussort, Impact of food processing and detoxification treatments on mycotoxin contamination, Mycotoxin Res. 32 (2016) 179–205.
[109] H. Bart, D. Evelyne, D. Els, Carry-over of some Fusarium mycotoxins in tissues and eggs of chickens fed experimentally mycotoxin-contaminated diets, Food Chem. Toxicol. 145 (2020) 111715.
[110] M. Britzi, S. Friedman, J. Miron, R. Solomon, O. Cuneah, J.A. Shimshoni, A. Shlosberg, Carry-over of aflatoxin B_1 to aflatoxin M_1 in high yielding Israeli cows in mid-and late-lactation, Toxins 5 (1) (2013) 173–183.
[111] C. Juan, L. González, J.M. Soriano, J.C. Moltó, J. Mañes, Accelerated solvent extraction of ochratoxin A from rice samples, J. Agric. Food Chem. 53 (24) (2005) 9348–9351.
[112] R. Perestrelo, P. Silva, P. Porto-Figueira, J.A. Pereira, C. Silva, S. Medina, J.S. Câmara, QuEChERS-Fundamentals, relevant improvements, applications, and future trends, Anal. Chim. Acta 1070 (2019) 1–28.
[113] P. Aqai, J. Peters, A. Gerssen, W. Haasnoot, M. Nielen, Immunomagnetic microbeads for screening with flow cytometry and identification with nano-liquid chromatography-mass spectrometry of ochratoxins in wheat and cereal, Anal. Bioanal. Chem. 400 (2011) 3085–3096.
[114] D. Jiang, C. Huang, L. Shao, X. Wang, Y. Jiao, W. Li, X. Xu, Magneto-controlled aptasensor for simultaneous detection of ochratoxin A and fumonisin B_1 using inductively coupled plasma mass spectrometry with multiple metal nanoparticles as element labels, Anal. Chim. Acta 1127 (2020) 182–189.
[115] V. Betina, Thin-layer chromatography of mycotoxins, J. Chromatogr. A 334 (1985) 211–276.
[116] P. Scott, J. Lawrence, W. Van Walbeek, Detection of mycotoxins by thin-layer chromatography: application to screening of fungal extracts, Appl. Microbiol. 20 (5) (1970) 839–842.
[117] R. Khan, F.M. Ghazali, N.A. Mahyudin, N.I.P. Samsudin, Chromatographic analysis of aflatoxigenic *Aspergillus flavus* isolated from Malaysian sweet corn, Separations 8 (7) (2021) 98.
[118] G.S. Shephard, Current status of mycotoxin analysis: a critical review, J. AOAC Int. 99 (4) (2016) 842–848.
[119] R. Montes, R. Segarra, M.Á. Castillo, Trichothecenes in breakfast cereals from the Spanish retail market, J. Food Compos. Anal. 27 (1) (2012) 38–44.
[120] H.U. Melchert, E. Pabel, Reliable identification and quantification of trichothecenes and other mycotoxins by electron impact and chemical ionization-gas chromatography–mass spectrometry, using an ion-trap system in the multiple mass spectrometry mode: candidate reference method for complex matrices, J. Chromatogr. A 1056 (1–2) (2004) 195–199.

[121] C. Juan, A. Ritieni, J. Mañes, Determination of trichothecenes and zearalenones in grain cereal, flour and bread by liquid chromatography-tandem mass spectrometry, Food Chem. 134 (4) (2012) 2389–2397.
[122] M. Sulyok, D. Stadler, D. Steiner, R. Krska, Validation of an LC-MS/MS-based dilute-and-shoot approach for the quantification of >500 mycotoxins and other secondary metabolites in food crops: challenges and solutions, Anal. Bioanal. Chem. 412 (2020) 2607–2620.
[123] E. Beltrán, M. Ibáñez, J.V. Sancho, F. Hernández, Determination of mycotoxins in different food commodities by ultra-high-pressure liquid chromatography coupled to triple quadrupole mass spectrometry, Rapid Commun. Mass Spectrom.: An International Journal Devoted to the Rapid Dissemination of Up-to-the-Minute Research in Mass Spectrometry 23 (12) (2009) 1801–1809.
[124] A.E. Urusov, A.V. Petrakova, M.V. Vozniak, A.V. Zherdev, B.B. Dzantiev, Rapid immunoenzyme assay of aflatoxin B_1 using magnetic nanoparticles, Sensors 14 (11) (2014) 21843–21857.
[125] A.E. Urusov, A.V. Zherdev, B.B. Dzantiev, Immunochemical methods of mycotoxin analysis, Appl. Biochem. Microbiol. 46 (2010) 253–266.
[126] R.J. Schneider, Environmental immunoassays, Anal. Bioanal. Chem. 375 (2003) 44–46.
[127] D. Tang, J.C. Sauceda, Z. Lin, S. Ott, E. Basova, I. Goryacheva, D. Knopp, Magnetic nanogold microspheres-based lateral-flow immunodipstick for rapid detection of aflatoxin B_2 in food, Biosens. Bioelectron. 25 (2) (2009) 514–518.
[128] D. Tang, Z. Zhong, R. Niessner, D. Knopp, Multifunctional magnetic bead-based electrochemical immunoassay for the detection of aflatoxin B_1 in food, Analyst 134 (8) (2009) 1554–1560.
[129] M. Pastucha, Z. Farka, K. Lacina, Z. Mikušová, P. Skládal, Magnetic nanoparticles for smart electrochemical immunoassays: a review on recent developments, Microchim. Acta 186 (2019) 1–26.
[130] S. Zhan, L. Zheng, Y. Zhou, K. Wu, H. Duan, X. Huang, Y.A. Xiong, Gold growth-based plasmonic ELISA for the sensitive detection of fumonisin B_1 in maize, Toxins 11 (6) (2019) 323.
[131] N. Beloglazova, E.S. Speranskaya, A. Wu, Z. Wang, M. Sanders, V.V. Goftman, S. De Saeger, Novel multiplex fluorescent immunoassays based on quantum dot nanolabels for mycotoxins determination, Biosens. Bioelectron. 62 (2014) 59–65.
[132] Q. Lu, X. Li, J. Zhao, J. Zhu, Y. Luo, H. Duan, Q. Zhao, Nanobody-horseradish peroxidase and-EGFP fusions as reagents to detect porcine parvovirus in the immunoassays, J. Nanobiotechnol. 18 (2020) 1–17.
[133] Y. Sheng, K. Wang, Q. Lu, P. Ji, B. Liu, J. Zhu, Q. Zhao, Nanobody-horseradish peroxidase fusion protein as an ultrasensitive probe to detect antibodies against Newcastle disease virus in the immunoassay, J. Nanobiotechnol. 17 (2019) 1–15.
[134] L. Barthelmebs, J. Jonca, A. Hayat, B. Prieto-Simon, J.L. Marty, Enzyme-linked aptamer assays (ELAAs), based on a competition format for a rapid and sensitive detection of Ochratoxin A in wine, Food Control 22 (5) (2011) 737–743.
[135] Y. Li, L. Sun, Q. Zhao, Aptamer-structure switch coupled with horseradish peroxidase labeling on a microplate for the sensitive detection of small molecules, Anal. Chem. 91 (4) (2019) 2615–2619.
[136] L. Sun, Y. Li, H. Wang, Q. Zhao, An aptamer assay for aflatoxin B_1 detection using Mg2+ mediated free zone capillary electrophoresis coupled with laser-induced fluorescence, Talanta 204 (2019) 182–188.
[137] Z. Wu, D. He, B. Cui, Z. Jin, E. Xu, C. Yuan, Q. Chai, Trimer-based aptasensor for simultaneous determination of multiple mycotoxins using SERS and fluorimetry, Microchim. Acta 187 (2020) 1–7.
[138] I. Bazin, N. Andreotti, A.I.H. Hassine, M. De Waard, J.M. Sabatier, C. Gonzalez, Peptide binding to ochratoxin A mycotoxin: a new approach in conception of biosensors, Biosens. Bioelectron. 40 (1) (2013) 240–246.
[139] D.T. Huang, H.J. Fu, J.J. Huang, L. Luo, H.T. Lei, Y.D. Shen, Z.L. Xu, Mimotope-based immunoassays for the rapid analysis of mycotoxin: a review, J. Agric. Food Chem. 69 (40) (2021) 11743–11752.
[140] Y. Xiong, Y. Leng, X. Li, X. Huang, Y. Xiong, Emerging strategies to enhance the sensitivity of competitive ELISA for detection of chemical contaminants in food samples, TrAC, Trends Anal. Chem. 126 (2020) 115861.
[141] J. Yan, Q. Shi, K. You, Y. Li, Q. He, Phage displayed mimotope peptide-based immunosensor for green and ultrasensitive detection of mycotoxin deoxynivalenol, J. Pharmaceut. Biomed. Anal. 168 (2019) 94–101.
[142] S.A. Piletsky, E.V. Piletska, B. Chen, K. Karim, D. Weston, G. Barrett, A.P. Turner, Chemical grafting of molecularly imprinted homopolymers to the surface of microplates. Application of artificial adrenergic receptor in enzyme-linked assay for β-agonists determination, Anal. Chem. 72 (18) (2000) 4381–4385.
[143] S. Wang, Z. Xu, G. Fang, Y. Zhang, B. Liu, H. Zhu, Development of a biomimetic enzyme-linked immunosorbent assay method for the determination of estrone in environmental water using novel molecularly imprinted films of controlled thickness as artificial antibodies, J. Agric. Food Chem. 57 (11) (2009) 4528–4534.
[144] I. Chianella, A. Guerreiro, E. Moczko, J.S. Caygill, E.V. Piletska, I.M.P. De Vargas Sansalvador, S.A. Piletsky, Direct replacement of antibodies with molecularly imprinted polymer nanoparticles in ELISA development of a novel assay for vancomycin, Anal. Chem. 85 (17) (2013) 8462–8468.
[145] L. Cenci, C. Piotto, P. Bettotti, A.M. Bossi, Study on molecularly imprinted nanoparticle modified microplates for pseudo-ELISA assays, Talanta 178 (2018) 772–779.
[146] H. Munawar, A.H. Safaryan, A. De Girolamo, A. Garcia-Cruz, P. Marote, K. Karim, S.A. Piletsky, Determination of fumonisin B_1 in maize using molecularly imprinted polymer nanoparticles-based assay, Food Chem. 298 (2019) 125044.
[147] T. Alsulami, N. Nath, R. Flemming, H. Wang, W. Zhou, J.H. Yu, Development of a novel homogeneous immunoassay using the engineered luminescent enzyme NanoLuc for the quantification of the mycotoxin fumonisin B_1, Biosens. Bioelectron. 177 (2021) 112939.
[148] S. Xu, G. Zhang, B. Fang, Q. Xiong, H. Duan, W. Lai, Lateral flow immunoassay based on polydopamine-coated gold nanoparticles for the sensitive detection of zearalenone in maize, ACS Appl. Mater. Interfaces 11 (34) (2019) 31283–31290.
[149] Y. Li, Z. Wang, R.C. Beier, J. Shen, D.D. Smet, S. De Saeger, S. Zhang, T-2 toxin, a trichothecene mycotoxin: review of toxicity, metabolism, and analytical methods, J. Agric. Food Chem. 59 (8) (2011) 3441–3453.
[150] J.X. Yan, W.J. Hu, K.H. You, Z.E. Ma, Y. Xu, Y.P. Li, Q.H. He, Biosynthetic mycotoxin conjugate mimetics-mediated green strategy for multiplex mycotoxin immunochromatographic assay, J. Agric. Food Chem. 68 (7) (2020) 2193–2200.
[151] S. Wu, L. Liu, N. Duan, Q. Li, Y. Zhou, Z. Wang, Aptamer-based lateral flow test strip for rapid detection of zearalenone in corn samples, J. Agric. Food Chem. 66 (8) (2018) 1949–1954.
[152] X. Tang, J. Wu, W. Wu, Z. Zhang, W. Zhang, Q. Zhang, P. Li, Competitive-type pressure-dependent immunosensor for highly sensitive detection of diacetoxyscirpenol in wheat via monoclonal antibody, Anal. Chem. 92 (5) (2020) 3563–3571.
[153] C. Zong, F. Jiang, X. Wang, P. Li, L. Xu, H. Yang, Imaging sensor array coupled with dual-signal amplification strategy for ultrasensitive chemiluminescence immunoassay of multiple mycotoxins, Biosens. Bioelectron. 177 (2021) 112998.
[154] F. Pei, S. Feng, Y. Wu, X. Lv, H. Wang, S.M. Chen, Z. Tong, Label-free photoelectrochemical immunosensor for aflatoxin B_1 detection based on the Z-scheme heterojunction of g-C3N4/Au/WO3, Biosens. Bioelectron. 189 (2021) 113373.
[155] D. Romanazzo, F. Ricci, G. Volpe, C.T. Elliott, S. Vesco, K. Kroeger, G. Palleschi, Development of a recombinant Fab-fragment based electrochemical immunosensor for deoxynivalenol detection in food samples, Biosens. Bioelectron. 25 (12) (2010) 2615–2621.
[156] B. Liu, J. Peng, Q. Wu, Y. Zhao, H. Shang, S.A. Wang, Novel screening on the specific peptide by molecular simulation and development of the electrochemical immunosensor for aflatoxin B_1 in grains, Food Chem. 372 (2022) 131322.
[157] M. Yin, X. Hu, Y. Sun, Y. Xing, G. Xing, Y. Wang, G. Zhang, Broad-spectrum detection of zeranol and its analogs by a colloidal gold-based lateral flow immunochromatographic assay in milk, Food Chem. 321 (2020) 126697.
[158] D. Calabria, M.M. Calabretta, M. Zangheri, E. Marchegiani, I. Trozzi, M. Guardigli, M. Mirasoli, Recent advancements in enzyme-based lateral flow immunoassays, Sensors 21 (10) (2021) 3358.
[159] P. Tripathi, N. Upadhyay, S. Nara, Recent advancements in lateral flow immunoassays: a journey for toxin detection in food, Crit. Rev. Food Sci. Nutr. 58 (10) (2018) 1715–1734.

[160] Y. Jin, Q. Chen, S. Luo, L. He, R. Fan, S. Zhang, Y. Chen, Dual near-infrared fluorescence-based lateral flow immunosensor for the detection of zearalenone and deoxynivalenol in maize, Food Chem. 336 (2021) 127718.
[161] W.B. Shim, M.J. Kim, H. Mun, M.G. Kim, An aptamer-based dipstick assay for the rapid and simple detection of aflatoxin B_1, Biosens. Bioelectron. 62 (2014) 288–294.
[162] V.L. Pereira, J.O. Fernandes, S.C. Cunha, Mycotoxins in cereals and related foodstuffs: a review on occurrence and recent methods of analysis, Trends Food Sci. Technol. 36 (2) (2014) 96–136.
[163] D.R. Thévenot, K. Toth, R.A. Durst, G.S. Wilson, Electrochemical biosensors: recommended definitions and classification, Anal. Lett. 34 (5) (2001) 635–659.
[164] A. Rico-Yuste, R. Abouhany, J.L. Urraca, A.B. Descalzo, G. Orellana, M.C. Moreno-Bondi, Eu (III)-Templated molecularly imprinted polymer used as a luminescent sensor for the determination of tenuazonic acid mycotoxin in food samples, Sensor. Actuator. B Chem. 329 (2021) 129256.
[165] G. Evtugyn, A. Porfireva, T. Kulikova, T. Hianik, Recent achievements in electrochemical and surface plasmon resonance aptasensors for mycotoxins detection, Chemosensors 9 (7) (2021) 180.
[166] W.W. Zhao, J.J. Xu, H.Y. Chen, Photoelectrochemical immunoassays, Anal. Chem. 90 (1) (2018) 615–627.
[167] Y. Lin, Q. Zhou, D. Tang, R. Niessner, D. Knopp, Signal-on photoelectrochemical immunoassay for aflatoxin B_1 based on enzymatic product-etching MnO_2 nanosheets for dissociation of carbon dots, Anal. Chem. 89 (10) (2017) 5637–5645.
[168] J.W. Lowdon, H. Diliën, P. Singla, M. Peeters, T.J. Cleij, B. van Grinsven, K. Eersels, MIPs for commercial application in low-cost sensors and assays–An overview of the current status quo, Sensor. Actuator. B Chem. 325 (2020) 128973.
[169] X. Hu, Y. Xia, Y. Liu, F. Zhao, B. Zeng, Determination of patulin using dual-dummy templates imprinted electrochemical sensor with PtPd decorated N-doped porous carbon for amplification, Microchim. Acta 188 (2021) 1–9.
[170] V. Ostry, F. Malir, J. Ruprich, Producers and important dietary sources of ochratoxin A and citrinin, Toxins 5 (9) (2013) 1574–1586.
[171] T. Villarreal-Barajas, A. Vázquez-Durán, A. Méndez-Albores, Effectiveness of electrolyzed oxidizing water on fungi and mycotoxins in food, Food Control 131 (2022) 108454.
[172] J.C. Young, T. Zhou, H. Yu, H. Zhu, J. Gong, Degradation of trichothecene mycotoxins by chicken intestinal microbes, Food Chem. Toxicol. 45 (1) (2007) 136–143.
[173] L. Afsah-Hejri, P. Hajeb, R.J. Ehsani, Application of ozone for degradation of mycotoxins in food: a review, Compr. Rev. Food Sci. Food Saf. 19 (4) (2020) 1777–1808.
[174] R. Čolović, N. Puvača, F. Cheli, G. Avantaggiato, D. Greco, O. Đuragić, L. Pinotti, Decontamination of mycotoxin-contaminated feedstuffs and compound feed, Toxins 11 (11) (2019) 617.
[175] S.A. Mir, B.N. Dar, M.A. Shah, S.A. Sofi, A.M. Hamdani, C.A. Oliveira, A.S. Sant'Ana, Application of new technologies in decontamination of mycotoxins in cereal grains: challenges, and perspectives, Food Chem. Toxicol. 148 (2021) 111976.
[176] R. Khan, F.M. Ghazali, N.A. Mahyudin, N.I.P. Samsudin, Co-inoculation of aflatoxigenic and non-aflatoxigenic strains of *Aspergillus flavus* to assess the efficacy of non-aflatoxigenic strains in growth inhibition and aflatoxin B_1 reduction, Agriculture 11 (3) (2021) 198.
[177] M. Ali, D.W. Sun, J.H. Cheng, O.J. Esua, Effects of combined treatment of plasma activated liquid and ultrasound for degradation of chlorothalonil fungicide residues in tomato, Food Chem. 371 (2022) 131162.
[178] O.J. Esua, J.H. Cheng, D.W. Sun, Functionalization of water as a nonthermal approach for ensuring safety and quality of meat and seafood products, Crit. Rev. Food Sci. Nutr. 61 (3) (2021) 431–449.
[179] M. Kiš, S. Milošević, A. Vulić, Z. Herceg, T. Vukušić, J. Pleadin, Efficacy of low-pressure DBD plasma in the reduction of T-2 and HT-2 toxin in oat flour, Food Chem. 316 (2020) 126372.
[180] X. Wang, Y. Han, J. Geng, A. Zhu, X. Wei, Q. Xiang, W. Zong, Removal of Alternaria mycotoxins exposed to different food components by cold plasma, Food Chem. 397 (2022) 133770.
[181] P. Puligundla, T. Lee, C. Mok, Effect of corona discharge plasma jet treatment on the degradation of aflatoxin B_1 on glass slides and in spiked food commodities, Lebensm. Wiss. Technol. 124 (2020) 108333.
[182] E. Wielogorska, Y. Ahmed, J. Meneely, W.G. Graham, C.T. Elliott, B.F. Gilmore, A holistic study to understand the detoxification of mycotoxins in maize and impact on its molecular integrity using cold atmospheric plasma treatment, Food Chem. 301 (2019) 125281.
[183] N. Misra, B. Yadav, M.S. Roopesh, C. Jo, Cold plasma for effective fungal and mycotoxin control in foods: mechanisms, inactivation effects, and applications, Compr. Rev. Food Sci. Food Saf. 18 (1) (2019) 106–120.
[184] M. Gavahian, P. Cullen, Cold plasma as an emerging technique for mycotoxin-free food: efficacy, mechanisms, and trends, Food Rev. Int. 36 (2) (2020) 193–214.
[185] G.J. Lee, G.B. Sim, E.H. Choi, Y.W. Kwon, J.Y. Kim, S. Jang, S.H. Kim, Optical and structural properties of plasma-treated *Cordyceps bassiana* spores as studied by circular dichroism, absorption, and fluorescence spectroscopy, J. Appl. Phys. 117 (2) (2015).
[186] X. Chen, Y. Qiu, J. Zhang, Y. Guo, Y. Ding, F. Lyu, Degradation efficiency and products of deoxynivalenol treated by cold plasma and its application in wheat, Food Control 136 (2022) 108874.
[187] T. Mehany, I. Khalifa, H. Barakat, S.A. Althwab, Y.M. Alharbi, S. El-Sohaimy, Polyphenols as promising biologically active substances for preventing SARS-CoV-2: a review with research evidence and underlying mechanisms, Food Biosci. 40 (2021) 100891.
[188] G.M. Hamad, A.A.A. Mohdaly, B.A. El-Nogoumy, M.F. Ramadan, S.A. Hassan, A.M. Zeitoun, Detoxification of aflatoxin B_1 and ochratoxin A using *Salvia farinacea* and *Azadirachta indica* water extract and application in meat products, Appl. Biochem. Biotechnol. 193 (10) (2021) 3098–3120.
[189] S.M. Sanzani, L. Schena, F. Nigro, A. De Girolamo, A. Ippolito, Effect of quercetin and umbelliferone on the transcript level of *Penicillium expansum* genes involved in patulin biosynthesis, Eur. J. Plant Pathol. 125 (2009) 223–233.
[190] A.C. Telles, L. Kupski, E.B. Furlong, Phenolic compound in beans as protection against mycotoxins, Food Chem. 214 (2017) 293–299.
[191] M.P. Salas, C.M. Reynoso, G. Céliz, M. Daz, S.L. Resnik, Efficacy of flavanones obtained from citrus residues to prevent patulin contamination, Food Res. Int. 48 (2) (2012) 930–934.
[192] R. Makhuvele, K. Naidu, S. Gbashi, V.C. Thipe, O.A. Adebo, P.B. Njobeh, The use of plant extracts and their phytochemicals for control of toxigenic fungi and mycotoxins, Heliyon 6 (10) (2020) e05291.
[193] V. Sharma, V. Patial, Food mycotoxins: dietary interventions implicated in the prevention of mycotoxicosis, ACS Food Science and Technology 1 (10) (2021) 1717–1739.
[194] J. Tian, X. Ban, H. Zeng, J. He, B. Huang, Y. Wang, Chemical composition and antifungal activity of essential oil from *Cicuta virosa* L. var. latisecta Celak, Int. J. Food Microbiol. 145 (2–3) (2011) 464–470.
[195] J. Cai, R. Yan, J. Shi, J. Chen, M. Long, W. Wu, K. Kuca, Antifungal and mycotoxin detoxification ability of essential oils: a review, Phytother Res. 36 (1) (2022) 62–72.
[196] A.K. Chaudhari, V.K. Singh, S. Das, J. Prasad, A.K. Dwivedy, N. Dubey, KImprovement of *in vitro* and *in situ* antifungal, AFB_1 inhibitory and antioxidant activity of *Origanum majorana* L. essential oil through nanoemulsion and recommending as a novel food preservative, Food Chem. Toxicol. 143 (2020) 111536.
[197] E. Kollia, C. Proestos, P. Zoumpoulakis, P. Markaki, Capsaicin, an inhibitor of ochratoxin A production by *Aspergillus* section *Nigri* strains in grapes (*Vitis vinifera* L.), Food Addit. Contam. 36 (11) (2019) 1709–1721.
[198] A. Kedia, A.K. Dwivedy, D.K. Jha, N.K. Dubey, Efficacy of *Mentha spicata* essential oil in suppression of *Aspergillus flavus* and aflatoxin contamination in chickpea with particular emphasis on the mode of antifungal action, Protoplasma 253 (2016) 647–653.
[199] K.N. Kumar, M. Venkataramana, J.A. Allen, S. Chandranayaka, H.S. Murali, H. Batra, V. Role of Curcuma longa L, Essential oil in controlling the growth and zearalenone production of *Fusarium graminearum*, LWT–Food Sci. Technol. 69 (2016) 522–528.
[200] A. Jebali, S.A. Yasini Ardakani, N. Sedighi, S. Hekmatimoghaddam, Nanocellulose conjugated with retinoic acid: its capability to adsorb aflatoxin B_1, Cellulose 22 (2015) 363–372.

[201] K.A. Abd-Elsalam, A.F. Hashim, M.A. Alghuthaymi, E. Said-Galiev, Nanobiotechnological strategies for toxigenic fungi and mycotoxin control, in: Food Preservation, Elsevier, 2017, pp. 337–364.
[202] D. Hu, S. Yu, D. Yu, N. Liu, Y. Tang, Y. Fan, A. Wu, Biogenic *Trichoderma harzianum*-derived selenium nanoparticles with control functionalities originating from diverse recognition metabolites against phytopathogens and mycotoxins, Food Control 106 (2019) 106748.
[203] M. Zahoor, F.A. Khan, Aflatoxin B_1 detoxification by magnetic carbon nanostructures prepared from maize straw, Desalination Water Treat. 57 (25) (2016) 11893–11903.
[204] B.A. Miu, A. Dinischiotu, New green approaches in nanoparticles synthesis: an overview, Molecules 27 (19) (2022) 6472.
[205] P. Horky, S. Skalickova, D. Baholet, J. Skladanka, Nanoparticles as a solution for eliminating the risk of mycotoxins, Nanomaterials 8 (9) (2018) 727.
[206] K. Pietrzak, M. Twarużek, A. Czyżowska, R. Kosicki, B. Gutarowska, Influence of silver nanoparticles on metabolism and toxicity of molds, Acta Biochim. Pol. 62 (4) (2015).
[207] Y. Zhang, M. Li, Y. Liu, E. Guan, K. Bian, Reduction of aflatoxin B_1 in corn by water-assisted microwaves treatment and its effects on corn quality, Toxins 12 (9) (2020) 605.