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EDITED BY
Limbikani Matumba,
Lilongwe University of Agriculture and Natural Resources, Malawi

REVIEWED BY
K. S. Yoha,
Entrepreneurship and Management - Thanjavur, India
Matthew D. Moore,
University of Massachusetts Amherst, United States

*CORRESPONDENCE
Abhay K. Pandey
abhaykumarpandey.ku@gmail.com
Mahesh K. Samota
mahesh.iari1@gmail.com
Ana Sanches Silva
anateress@gmail.com

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Fungal mycotoxins in food commodities: present status and future concerns

Abhay K. Pandey[1]*, Mahesh K. Samota[2]*, Abhishek Kumar[3], Ana Sanches Silva[4,5]* and Nawal K. Dubey[6]

[1]Department of Mycology and Microbiology, Tea Research Association, North Bengal Regional R & D Center, Nagrakata, India, [2]Horticulture Crop Processing Division, ICAR-Central Institute of Post-Harvest Engineering and Technology, Abohar, India, [3]Department of Plant Pathology, CCS Haryana Agricultural University, Hisar, India, [4]National Institute for Agricultural and Veterinary Research (INIAV), I. P., Rua dos Lagidos, Lugar da Madalena, Vila do Conde, Portugal, [5]Center for Study in Animal Science (CECA), ICETA, University of Oporto, Oporto, Portugal, [6]Department of Botany, Banaras Hindu University, Varanasi, India

Mycotoxins are toxic secondary metabolites produced by fungi when they colonies the foodstuffs. These are potent toxins having severe health consequences in people, being mutagenic, teratogenic, and carcinogenic. In agricultural commodities, the contamination of mycotoxins is more prevalent. Several fungi can produce mycotoxins on agricultural products during harvest or in postharvest, and they have significant adverse effects on both animal and human beings. The most prevalent mycotoxins found in food commodities are aflatoxins and ochratoxins produced by *Aspergillus* species, ochratoxins and patulin produced by *Penicillium*, as well as fumonisins, deoxynivalenol, and zearalenone produced by *Fusarium* species. Worldwide, fumonisins, patulin, aflatoxins, and ochratoxins, among others, are responsible for numerous acute and chronic diseases in people and domestic animals. In food commodities, mycotoxins have been quantified and detected using various analytical methods. Besides, mycotoxins occurrence in food commodities were decontaminated through many potential approaches, such as physical, chemical, and biological methods. This review summarizes the findings of 30years of research into mycotoxins in major commercial food crops including wheat, maize, sorghum, pearl millet, peanut, oat, pulses, barley, oilseeds, rice, and fruits and fruit juices. We also discuss the detection methods of major mycotoxins, available decontamination strategies along with their disadvantages and knowledge gaps. It is anticipated that data from meticulous studies on mycotoxins in food commodities will help in the development of safer food and in setting priorities for future research.

KEYWORDS

ochratoxin, food commodities, aflatoxins, fumonisins, physical methods, essential oils

Introduction

An estimated 30 to 50% of food commodities are lost during pre-harvest or post-harvest globally, which does not only threaten global food security but wastes 1.47–1.96 Gha of arable land, 0.75–1.25 trillion cubic meters of water and 1 to 1.5% of global energy (Fox and Fimeche, 2013). The pre-harvest and postharvest losses in food commodities may occur due to attack by several biotic and abiotic factors. In storage system, fungal bio-deterioration of stored food commodities is a chronic problem in tropical hot and humid climates. Harvested food grains

can be contaminated by different genera of fungi such as *Aspergillus, Alternaria, Fusarium, Cladosporium, Penicillium*, *Mucor*, and *Rhizopus* (Mateus et al., 2021). Under specific conditions, some fungi can produce toxic metabolites called mycotoxins, leading to food contamination. The major toxin-producing moulds include genera of *Aspergillus*, *Fusarium*, *Penicillium*, and *Alternaria* (Khodaei et al., 2021; Pandey et al., 2022).

Human and livestock health is adversely affected by consumption of mycotoxins contaminated food products, which affect the marketability of food commodities and raise food safety concerns (Mateus et al., 2021). It is estimated that more than five billion people are exposed to mycotoxins daily by unknown pathways and consume contaminated foods every day (Khodaei et al., 2021). Taking mycotoxins through food can lead to intoxication, known as mycotoxicosis (Tanaka et al., 2007). Mycotoxicosis occurs when a mycotoxin leads to acute or chronic toxicity involving hepatotoxicity, cytotoxicity, teratogenicity, neurotoxicity, mutation, and carcinogenicity. At cellular levels, mycotoxins inhibit DNA and RNA synthesis by interacting with nucleic acids (Smith et al., 2007). In the past years, several reviews published on occurrence of mycotoxins in various food commodities (Tola et al., 2016; Lee and Ryu, 2017; Khodaei et al., 2021). However, these are either crop/country specific or discusses only occurrence or management strategies. In this review, the findings from research data collected over the past 30 years are discussed, including mycotoxins in major commercially important food crops like wheat, maize, sorghum, pearl-millets, peanut, oat, pulses, barley, oilseeds, rice, and fruits. Detection methods for major mycotoxins and available decontamination strategies are also discussed along with their limitations and knowledge gaps.

Classification of foodborne mycotoxins

The mycotoxins produced by fungi are majorly classified as aflatoxins (AFs), ochratoxin A (OTA), patulin (PT), sterigmatocystin (STC), trichothecenes (TCTs) fumonisins (FBs), deoxynivalenol (DON), zearalenone (ZEA), alternariol (AOH), tenuazonic acid, and alternariol monomethyl ether. Table 1 provides information about some important mycotoxins, food commodities they are contaminating and their toxic effects. Aflatoxin is an enormously toxic mycotoxin and is produced worldwide mainly by *A. flavus* and *A. parasiticus* (Pandey et al., 2016). It includes four major types, such as B1, B2, G1, and G2. It has been determined that *A. flavus* produces B toxins, the most common of which is B1, which is carcinogenic and genotoxic (Payne and Brown, 1998; Abbas et al., 2008). Compared to other crops, maize and cotton have higher levels of AFs produced by *A. flavus* (Hell et al., 2000); nevertheless, in groundnut (peanut) AF derived from *A. parasiticus* is common (Kaaya et al., 2006). Another mycotoxin, ZEA is also known as F-2 mycotoxin. Many species of *Fusarium* produce DON, T2, and HT-2 toxins, ZEA, and diacetoxyscirpenol (DAS), toxic chemicals of considerable concern to livestock and poultry producers (Kuiper-Goodman et al., 1987). A number of food products can be affected by these toxins as demonstrated in Table 1. In pigs, especially, it can cause infertility, abortion, and other breeding problems (Kuiper-Goodman et al., 1987).

Fumonisins are mycotoxins produced by *Fusarium* and are composed of FB1 and FB2. *Fusarium verticillioides* mainly attack maize, wheat, and many other grains, produces FB1, which is the most prevalent member of this family of toxin-producing *Fusarium* moulds. There is also evidence that *F. verticillioides* and *F. moniliforme* produce FB2, which is structurally similar to FB1 (Polišenská et al., 2020). Compared with FB1, FB2 is more cytotoxic and inhibits acylsphingosine transferase. Maize and other commodities are also contaminated by FB2. There have been reports of 15 different FBs to date, although most have not been shown to occur in nature (Polišenská et al., 2020). As far as ochratoxins are concerned, three types of ochratoxins are present in food commodities, namely OTA, OTB, and OTC. OTA is the most prevalent mycotoxin found in foodstuffs, produced by *Penicillium verrucosum* and species of *Aspergillus* such as *A. carbonarius* and *A. ochraceus* (Al-Anati and Petzinger, 2006). Consumption of OTA-contaminated food products, such as grains, coffee, pork products, grapes, and grape products, can result in human acquaintance (Richard et al., 1999). Besides, *Aspergillus*, *Byssochlamys*, and *Penicillium* produce PT, which is typically found in rotten apples. It has been shown that PT possesses antimicrobial activity against some microorganisms. Health studies have caused several countries to regulate PT's quantity in commodities as a result of health risks.

Mycotoxin regulations in food commodities

In order to prevent their detrimental effects on humans, mycotoxins are regulated by maximum permissible levels in food (Claeys et al., 2020). The contents of mycotoxins in food commodities have been restricted in several countries (Puel et al., 2010). Additionally, a number of national and international agencies, including the Food and Agriculture Organization, World Health Organization, EU Commission, and Codex Alimentarius Commission, have established regulations regarding different types of mycotoxins present in different foods aimed at protecting consumers (Adeyeye, 2016). Most countries have no specific limits on specific foods or food products, but all food products are subject to general regulations. There are, however, some countries in Europe and the USA that have legislated dietary limits for specific foods. Among mycotoxins, AFs have potent genotoxic, carcinogenic, and immunosuppressive effects on people. Therefore, in most food commodities, government agencies have established maximum levels of aflatoxins, including AFB1 (Bhat and Reddy, 2017). The maximum limits (μg/kg) of important fungal mycotoxins in major food commodities that were legislated are summarized in Table 2.

Methods of detecting mycotoxins

Mycotoxins are toxic and poisonous, can occur even with the very small quantities in food commodities, and consumption of such food products causes several health risks. Therefore, there is a need to analysis and quantification of mycotoxins by sensitive and accurate methods (Le et al., 2021) so that they can reduce before consumptions. For the quantification and detection of mycotoxins in foodstuffs, several analytical methods have been adopted (Berthiller et al., 2017). The most significant ones are discussed in this review, and their advantages and disadvantages are summarized in Table 3.

TABLE 1 List of important mycotoxins, most prone food commodities to be contaminated by mycotoxins and their principal toxic effects.

Mycotoxins	Related moulds	Most prone food products to be contaminated	Symptoms/toxicology	References
Aflatoxins	*Aspergillus parasiticus*, *A. nomius,* and *A. flavus*	Grain, cherries, strawberries, groundnut, raspberries, maize, peanuts, maize, cotton, pearl millet, sorghum, pistachios, chillies, cassava, oil seeds, spices, and dried fruits	Depressed immune response, liver tumours, Liver necrosis, reduced growth, carcinogenic, hepatotoxic, mutagenic, teratogenic, vomiting, and pulmonary convulsions	Liu et al. (2006)
Cyclopiazonic acid	*A. flavus, A. oryzae, A. versicolor, A. tamarii. P. patulum, P. verrucosum, P. camembertii, P. cyclopium, Penicillium griseofulvum*, and *P. puberulum*	Peanuts, maize, cheese etc.	Neurotoxin, cytotoxicity, weight loss, immunotoxicity, diarrhea, muscle, nausea, viscera necrosis, and convulsions	Gonçalez et al. (2008)
Deoxynivalenol, Vomitoxin, Zearalenone	*Fusarium graminearum* and *F. subglutinans*	Wheat, maize, oats, maize, rice, sorghum, and barley	Diarrhoea, vomiting, decreased weight gain, feed refusal, infertility, hepatotoxic, genotoxic, immune-toxic, hemato-toxic, and oestrogenic effect	Nakagawa et al. (2011)
Fumonisin B1 and Fumonisin B2	*F. moniliforme* and *F. verticillioides*	Maize, rice, and wheat	Porcine pulmonary edema, equine leukoencephalomalacia, kidney disease, liver tumor, hepatotoxic, nephrotoxic, cytotoxic, and oesophagal cancer	Topi et al. (2021)
Trichothecenes	*F. culmorum, Trichoderma*, *F. graminearum, F. poae*, *Cephalosporium*, and *Trichothecium*	Wheat, oats, and maize	Food toxic aleukia, necrosis, oral lesion in broiler chickens, weight loss, vomiting, diarrhoea haemorrhages, growth retardation, cartilage tissue damage, fever, dizziness, fever, and neurotoxic.	Jimenez and Mateo (1997)
Ochratoxin	*A. ochraceus, P. verrucosum*, and *A. carbonarius*	Wheat, spices, grapes, and coffee	Various poultry symptoms; porcine nephropathy, genotoxicity, immunotoxicity, embryotoxicity teratogenicity, neurotoxicity, protein, RNA, and DNA synthesis inhibitor	Iqbal et al. (2018)
Patulin and Citrinin	*P. expansum*	Apple, orange, grapes, and related products	Kidney damage, nephrotoxic, immunotoxicity, teratogenic, hepatotoxic, and foetotoxic	Saxena et al. (2008); Oteiza et al. (2017)
Sterigmatocystin	*A. parasiticus*, *A. versicolor*, *A. flavus, A. nidulans, A. rugulosus, A. rubber, A. chevalieri, P. camembertii, A. amsyelodami, P. griseofulvum, P. communer*	Maize, rice, wheat, and hay	Carcinogenic, mutagenic, immunotoxicity, cytotoxicity, diarrhea, nausea, and weight loss.	Iqbal et al. (2018)
Alternaria toxins: alternariol, tenuazonic acid and others	*Alternaria* species	Grains, oil seeds, spices, and various fruits and vegetables	Cytotoxic, genotoxic, teratogenic, mutagenic, fetotoxic, and dermal toxicity	Dong et al. (2019)

Extraction and purification of mycotoxins

Extraction and purification of mycotoxins from foods samples using appropriate solvents is the first step of preparation of samples. QuEChERS (Quick, Easy, Cheap, Effective, Rugged, and Safe) is the method used for the detection of mycotoxins in different matrices. In this method, toxin is firstly extracted with acetonitrile-water, then added inorganic salts for induction of liquid–liquid partitioning, and mycotoxins are moved to the organic phase (Gonzalez-Jartin et al., 2019). QuEChERS has been used in berries-derived jam and juice for

TABLE 2 The maximum limits (μg/kg) established for major mycotoxins in some countries/regions for all food commodities.

Countries	Food commodities	Mycotoxins	References
Brazil	All foods	15 (AFB1)	Aiko and Mehta (2015)
Chile	All foods	200 (ZEA)	Ji et al. (2019)
China	All foods	30 (AFB1)	Ji et al. (2019)
EU	All foods	5 (AFB1); 10 (TAF); 15 (OTA)	EC (2006)
India	All foods	30 (AFB1)	Anukul et al. (2013)
Indonesia	All foods	35 (AFs), 20 (AFB1)	Ji et al. (2019)
Japan and Vietnam	All foods	10 (AFs)	Anukul et al. (2013)
Malaysia	All foods	35 (TAFs)	Srianujata (2011)
Singapore and Australia	All foods	5 (AFs)	Anukul et al. (2013), Mazumder and Sasmal (2001)
Sri Lanka	All foods	30 (TAFs)	Anukul et al. (2013)
Thailand	All foods	20 (AFs); 30–1,000 (ZEA)	Anukul et al. (2013), Mazumder and Sasmal (2001)
USA	All foods	20 (AFs); 1,000 (ZEA); 2000 (FBs)	Ji et al. (2019), Mazumder and Sasmal (2001)
EU	Maize oil	400 (ZEA), 1,000 (FBs)	European Commission (EU) (2006), Goud et al. (2020)
China	Peanut oil	20 (AFB1)	Selvaraj et al. (2015)
Cuba	Fruits	40 (PAT)	Cai et al. (2020)
Israel	Apple Juice	50 (PAT)	Nascimento and Taniwaki (2023)
Canada	Fruits and Fruit Juice	50 (PAT)	Canada (2020)
India	Apple Juices	50 (PAT)	Shukla et al. (2014)
Japan	Apple Juices	30 (PAT)	Li and Beghin (2014)
European Union	Tomato juices	30 (PAT)	Van Egmond and Jonker (2008)

the analysis of mycotoxins such as AFs, OTA, etc. (Juan et al., 2017). Liquid – Liquid extraction (LLE) method is based on the different solubility of toxins in the organic phase and aqueous phase. LLE has been also applied for the analysis of AFs and OTA (Andrade et al., 2013; Turner et al., 2015). Liquid–solid extraction (SLE) is the method based on weighing of homogenized sample in extraction solvent followed by agitating it in a shaker. This has been used for the extraction of mycotoxins associated with cereals (Rubert et al., 2012; Xie et al., 2016). Pressurized Liquid Extraction (PLE) or Accelerated Solvent Extraction (ASE), is the method performed at increased temperature (100–180°C) and pressure (1,500–2,000 psi) in a vessel that improved extraction of mycotoxins. This method was used to detect mycotoxins in tomato samples (Rico-Yuste et al., 2018; Miklos et al., 2020). In another study, supercritical Fluid Extraction (SFE) is used for the extraction of non-polar organic molecules such as ZEA detection in maize flour (Zougagh and Ríos, 2008). The advantage of the SFE method is that it eliminates and minimized the use of organic solvents by supercritical CO_2 (Xie et al., 2016). Extraction is required to release the mycotoxins from the matrix and eliminate the effect of matrix and substances which can interfere with the detection of mycotoxins.

The next step is the purification of the extract that increases the specificity, sensitivity, and accuracy of the quantification. The most common two methods used for mycotoxins purifications are solid-phase extraction (SPE) and immunoaffinity columns (IAC) (Alshannaq and Yu, 2017). The SPE is a rapid and efficient method and involves the absorbents (octadecylsilyl (C18), amino-propyl (NH2), multi-walled carbon nanotubes (MWCNTs), and silica gel), which are packed in cartridges and absorbs the mycotoxins (Wang M. et al., 2016; Huertas-Perez et al., 2017; Jiang et al., 2018). SPE has been used for the purification of type A TCTs in rice, maize, and wheat (Dong et al., 2015) and ZEA in maize (Han et al., 2017). In the case of IAC, for selective mycotoxins detection, specific monoclonal antibodies are used, and the target mycotoxin is bound by specific antibodies on the column. The mycotoxins are eluted from the column with pure acetonitrile or methanol (Liu et al., 2018). IAC was used in the analysis of OTA, ZEA, and AFs in wheat bran (Irakli et al., 2017), OTA, AFs, and *Fusarium* toxins in maize (Lattanzio et al., 2007) and cereals (Lattanzio et al., 2014).

Detection of mycotoxins

Since the discovery of the mycotoxins, many different methods have been used to analyze the mycotoxins but the most common methods for mycotoxin analysis and detection include chromatographic techniques, immunoassays methods, or rapid strip screening tests (Zhang et al., 2018; Janik et al., 2021; Le et al., 2021). Methods belonging to the chromatographic group are aimed at quantitatively determine mycotoxins because of their potential to accurately detect, identify and quantify multiple toxins (Agriopoulou et al., 2020), and involve different types of chromatography: Liquid chromatography–tandem mass spectrometry (LC–MS/MS) or gas chromatography-tandem mass spectrometry (GC–MS/MS). Thin-layer chromatography (TLC) and high-performance liquid chromatography (HPLC) coupled to diode array, fluorescence, and UV-detectors (Zhang et al., 2018; Janik et al., 2021).

TLC is an effective method for qualitative and quantitative detection and analysis of many mycotoxins due to low costs, simplicity, and UV light fluorescent spots (Janik et al., 2021). But has low sensitivity and poor accuracy, which makes quantification very demanding (Singh and Mehta, 2020). The reliable separation capability

TABLE 3 Application, advantages, and disadvantages of mycotoxin detection methods.*

Methods	Advantages	Disadvantages
Immunoaffinity column	Good specificity and sensitivity	Costly and detect only one mycotoxin at a time
Solid-phase extraction	Cos-effective, more selective, long shelf life and easy in preparation	Not specific and takes longer time
Multifunctional columns	Long shelf life and appropriate for concurrent detection	Vulnerable to the matrix effect
Thin layer chromatography	Quick, simple, and qualitative method	Low sensitivity and no quantification
Enzyme-linked immunosorbent assay	Sample preparation easy, low-cost, and appropriate for rapid screening	Cross-reactivity and chances of false positive or negative results
Dual-label time-resolved fluoroimmunoassay	Good sensitivity, nonradioactive and high intensity of fluorescence	Cross-reactivity, and possible false positive or negative results
Multiplex flow cytometric microsphere immunoassay	No cross-interaction, suitable for simultaneous analysis of mycotoxins	Poor sensitivity and require suitable multi-mycotoxin clean-up step and specific probes
Immunochip	Excellent sensitivity, visual semi-quantitative, and appropriate for concurrent analysis of mycotoxins	Costly in analytical cost, complex labelling process and need professional experts
Immuno-rotary biosensor	Low cost, quick, accurate, and good specificity	Low stability and short useful life
Lateral flow immunoassay	Quick, easy, one-step, and cost-effective	Low sensitivity, and quantification negligible
Surface plasmon resonance	Quick speed, and no need for competition or labelled reagents	Temperature sensitive and samples components, probable false positive or negative results
Electronic nose	Sample handling not required, quick, preciseness, and high-flux	Low sensitivity, costly, and short useful life
High-performance liquid chromatography	Excellent sensitivity, repeatability, and selectivity, and suitable for concurrent multiple mycotoxins detection	Require costly equipment, and need clean-up step
Gas chromatography mass spectrometry	Quick, good sensitivity and repeatability	Require costly equipment, derivatization and clean-up step
Liquid chromatography tandem mass spectrometry	Good sensitivity, repeatability, and reproducibility, appropriate for concurrent analysis of mycotoxins and derivatization not required	Costley equipment, samples require clean-up step, and matrix effects

*Source: Xie et al. (2016), Alshannaq and Yu (2017), Juan et al. (2017), Rico-Yuste et al. (2018), Miklos et al. (2020).

of liquid chromatography (LC) coupled with the sensitivity of tandem mass spectrometry has positioned it as an effective analytical technique for the simultaneous detection and quantification of mycotoxins in a range of matrices (Adebo et al., 2018; Gbashi et al., 2019). The LC technique have been developed to overcome the constraints of the TLC method and it is applied for the detection of non-volatiles, high polarity, and thermally labile mycotoxins (Singh and Mehta, 2020; Yang et al., 2020). HPLC with different adsorbents and detectors *viz.* fluorescent (FLD) and UV visible (UV) depends on the presence of chromophore used for mycotoxin analysis. Sometimes directly detected in HPLC-FLD using natural fluorescence (e.g., AFs and OTA) in rice (Zinedine et al., 2007).

The MS/MS combination with LC (LC–MS/MS) provides a good analytical tool with high sensitivity, selectivity, and reliability (Malachova et al., 2018; Pascale et al., 2019). LC–MS/MS method has been effectively used for the detection of mycotoxins in a mixture of spices and herbs (El Darra et al., 2019). LC–MS/MS-based multi methods have gained growing relevance, as they allow rapid detection or even quantification of multiple-mycotoxins in several food groups and feedstuffs (Zhang K. et al., 2017). In order to quantification of different mycotoxins (AFB1, B2, G1, G2, OTA, DON, ZEA, T-2 toxin, and HT-2 toxin) for grain legumes, LC–MS/MS was used (Kunz et al., 2020). Tebele et al. (2020) were detected 12 mycotoxins in wheat, maize, and sorghum, including α-zearalenol (α-ZEL), FB3, FB1, tenuazonic acid (TeA), OTB, DON, OTA, 3-acetyldeoxynivalenol, sterigmatocystin (STG), 15-acetyldeoxynivalenol, cyclopiazonic acid (CPA), and aflatoxin B2 using liquid chromatography–tandem mass spectrometry.

When the rapid detection of mycotoxin is required, immunological tools are used such as lateral flow immunoassay (LFIA; Wolf and Schweigert, 2018; Lattanzio et al., 2019) and enzyme-linked immunosorbent assay (ELISA; Hendrickson et al., 2018). Detection depends on explicit monoclonal and/or polyclonal antibodies developed against these toxins (Thanushree et al., 2019) Because of simplicity and cheapness coupled to sensitivity and selectivity, immunoassays are preferably employed for the first level screening and survey studies on mycotoxin contamination. ELISA-based kits are commercially available for all regulated mycotoxins and provide the most-used analytical tool for assuring food safety through the food chain (Pereira et al., 2014). Besides, immunochemical-based tests in diverse formats are continuously developed to provide rapid, portable, and easy to operate systems (Zhang et al., 2015). Among these, the immunochromatographic test (ICT) technology plays the lead role and has been widely applied for the visual yes/no detection of mycotoxins and for their semi-quantification (Majdinasaba et al., 2015).

In recent years, biosensors such as electrochemical, optical, and piezoelectric have also been used to identify mycotoxins in foodstuffs (Younis et al., 2020). Biosensors have been classified as surface acoustic wave and optical-based on the operational principle. Multi-mycotoxins have been analysed in a single step by immunochemical biosensors (Magan, 2006). Surface Plasmon Resonance (SPR) and nanoparticle-based biosensor techniques are based on changes in refractive indices and called 'label-free' tools. SPR technique involves optical real-time detection of multiple analytes. A new fluorescence polarization method using near-infrared fluorescence sensors has also been developed that showed a great potential in fluorescence detection and measurement. Through this method, an antibody-binding fluorescence-labelled PT derivative exhibits an increase in fluorescence polarization emissions (Melinte et al., 2022). This method can detect PT in food commodities ranges from 6 to 102 μg/L (Melinte et al., 2022). This technique relied on the unique properties of crystals or quartz. Zhang W. et al. (2017) have developed a nano-sensor that discriminates mycotoxins selectively using manganese-doped ZnS quantum dots. Researchers have been focusing on restoring biosensor activity after use in recent years. For example, Soldatkin et al. (2017) pursued inhibitory action of PT, and developed a conduct metric urease-based biosensor. Because of its high PT sensitivity, strong selectivity, and high signal repeatability, this biosensor can be used to assess PT concentrations in apple juice beyond 50 g/L. As a technique to enhance biosensor signal transmission, lanthanide-doped rare earth-doped up-conversion nanoparticles (UCNPs) have attracted much attention (Loo et al., 2019). It offers several advantages over conventional down-conversion luminescent devices to use NIR-to-visible up-conversion nanoparticles (UCNPs). This technology has a low autofluorescence background which improves the signal-to-noise ratio, low toxicity, high photostability, tunable wavelength, high Stokes offsets, and deep tissue infiltration. Mycotoxins are detected in food using biosensors linked to transducers that use enzymes, aptamers, and antibodies as tools for recognition. Due to their remarkable ability to recognize mycotoxins at low dosages and modify their absorption properties, aptamers are becoming increasingly popular. Food industry applications can use them for on-line control of mycotoxins including PT. The main challenges of biosensors are the limited stability of the bio-recognition component (which affects the long-term storage stability of the biosensors), poor selectivity, particularly in enzyme inhibition-based biosensors, and the high cost of antibodies compared to synthetic recognition elements (Burcu Aydın et al., 2020).

Another emerging field for the detection of mycotoxins is nanotechnology. For detection of multiple mycotoxins, the analyte is labeled with probes such as nano-silver, graphene, and magnetic nanoparticles (Zinedine et al., 2006). The electronic nose is a rapid method based on aromas and ordour of the food. Fungal contamination of foods formed mycotoxins implies volatile by-products and characterized by GC–MS and correlated with fungal activity (Yao et al., 2015). In addition, recently non-destructive tools such as machine vision systems have emerged for the detection of toxins and identification of fungal contamination in food materials (Vithu and Moses, 2016). The combination of spectroscopy and NIR hyper-spectral imaging works in the wavelength range between 700 and 2,500 nm to differentiate between beneficial and fungal contaminated samples and detects AFs and OTA in foods (Senthilkumar et al., 2016).

In addition to the standard methods described above, several other methods have been developed such as electronic nose, fluorescent polarization, aggregation-induced emission, and molecularly imprinted polymers. The electronic nose (e-nose) was based on the chemical changes in the volatile organic compounds (VOCs) caused by the fungal species and observed the correlation between mycotoxin concentration and VOCs in food commodities (Ottoboni et al., 2018). The e-nose has been used for the detection of FBs and AFs in maize (Ottoboni et al., 2018), DON in durum wheat (Lippolis et al., 2014), and wheat bran (Lippolis et al., 2018). Fluorescent Polarization (FP) has been used in the detection of mycotoxins in various foodstuffs, such as ZEA in maize (Zhang K. et al., 2017), AFB1 in maize (Zhang et al., 2018), and OTA in rice (Huang X. et al., 2020). The Aggregation-Induced Emission (AIE) dye-based apta sensor has been successfully developed for OTA detection in wine and coffee (Zhu et al., 2019) and AFB1 in peanut oil and broad bean sauce (Xia et al., 2018). During molecular imprinting, cross-linked polymers are formed between functional monomer and template as mycotoxins (Krska et al., 2005). Molecularly Imprinted Polymers (MIPs) have been developed for the detection of AFB1 in wheat (Guo et al., 2019) and ZEA in cereals (Huang Z. et al., 2020).

Occurrence of mycotoxins in food commodities

There are various mycotoxigenic fungi that cause contamination of agricultural commodities, which are important food and feed sources. The rapid evolution of agricultural technology has contaminated food products directly like pulses, cereals, vegetables, and fruits with mycotoxins. Tropical regions seem to have a greater problem than temperate regions, but no place in the world can be considered mycotoxin-free. This may be related to the transportation of various foodstuffs from one country to another. In particular, following foodstuffs have been discovered to contain mycotoxins naturally. The detection levels of mycotoxins in various food commodities are also documented in Table 4.

Rice (*Oryza sativa* L.)

Rice (paddy) is one of the most important food crops worldwide. Mycotoxin contaminations are greatly influenced the production of rice by the climate and storage conditions. Mycotoxigenic fungi in rice are believed to be species of *Aspergillus*, *Fusarium*, and *Penicillium*. As a result of these fungal infections, grains and glumes discolor, lose viability, quality, and become contaminated with toxins. In rice, presence of AFs, OTA, cyclopiazonic acid, FBs, TCT, ZEA, DON, CT, gliotoxin, and STC have been reported by several investigators (Gummert et al., 2009; Reddy et al., 2009a; Siruguri et al., 2012). Date back, Jayaraman and Kalyanasundaram (1990) found that AFB1 content of parboiled rice bran and rice bran samples was up to 35%. According to a study conducted in 1990, rice samples contained more AFs (184 to 2,830 μg/kg) than wheat and maize samples (Pande et al., 1990). In 36 samples of de-husked brown rice, Liu et al. (2006) found AFB1, AFB2, AFG1, and AFG2 which levels ranged from 0.99 to 3.87 μg/kg. Researchers in India have found 67.8% AFB1-positive rice and paddy samples out of the total samples examined, with toxin levels

TABLE 4 Detection levels of mycotoxins in major food commodities.

Food commodity	Types of mycotoxins detected	Level of mycotoxins	Reference
Rice	OTA	8.5 μg/kg	Iqbal et al. (2016)
	CIT	0.1 to 0.2 μg/kg	Nganou Donkeng et al. (2022)
	AFB1	8.91 μg/kg	Iqbal et al. (2016)
	FUMs	4,361 μg/kg	Wielogorska et al. (2019b)
	DON	1,607 μg/kg	Khodaei et al. (2021)
Maize	AFB1	188 μg/kg	Aristil et al. (2020)
	DON	963 μg/kg	Kos et al. (2020)
	ZEN	163 μg/kg	Kos et al. (2020)
	OTA	1,662 μg/kg	Do et al. (2020)
	FUMs	43,296 μg/kg	Bertuzzi et al. (2020)
Wheat	DON	17,753 μg/kg	Xu et al. (2019)
	ZEA	132.7 ng/g	Rai et al. (2018)
	AFs	9 μg/kg	Hassan et al. (2019)
	OTA	2.1478 μg/kg	Karoki et al. (2018)
Sorghum	AFB1	2 μg/kg	Lahouar et al. (2018)
	FUMs	6,198 μg/kg	Onyedum et al. (2020)
	FB1	274 μg/kg	Ssepuuya et al. (2018)
	Alternariol	212 μg/kg	Ssepuuya et al. (2018)
	OTA	1.0311 μg/kg	Karoki et al. (2018)
Barley	T-2 plus HT-2 toxin	107.7 μg/kg	Pernica et al. (2022)
	DON	43,900 μg/kg	Drakopoulos et al. (2021)
	AOH	712 to 2,201 μg/kg	Castañares et al. (2020)
	Ergot alkaloids	121 to 555 μg/kg	Shi et al. (2019)
Pearl millet	Fumonisins	6–29 μg/kg	Vismer et al. (2015)
	OTA	405 μg/kg	Senthilkumar et al. (2021)
	AFB1	106 μg/kg	Houissa et al. (2019)
	Moniliformin	21,400 mg/kg	Vismer et al. (2019)
Pulses	AFTs in chickpea	11.2 ppb	Nazir et al. (2019)
	AFB1 in chickpea	167.4 μg/kg	Mohana et al. (2017)
	OTA in white beans	157 μg/kg	Kunz et al. (2020)
	DON	2.61–21.59 μg/kg	Carballo et al. (2018)
Oilseed crops	STC in soybean	13 μg/kg	Niyibituronsa et al. (2018)
	Tenuazonic acid in sunflower	12.8 μg/kg	Tölgyesi et al. (2020)
	DON in soybean	500–5,000 ng/g	Chiotta et al. (2020)
Groundnut	AFB1	117.8 μg/kg	Oyedele et al. (2017)
	AFB1	501 μg/kg	Matumba et al. (2015)
Fruits and fruit juice	TeA	7830.19 μg/kg	Fan et al. (2022)
	TEN	3397.33 μg/kg	Fan et al. (2022)
	AOH	3.6 to 44.2 μg/kg	Dong et al. (2019)
	PAT	254.1–410.2 μg/kg	Iqbal et al. (2018)

ranged from 0.5 to 38.5 μg/kg (Reddy et al., 2009a). Further, samples collected from six districts in Punjab by Siruguri et al. (2012) revealed that PAU 201 variety of stored rice had AFB1 levels below 15 μg/kg.

In Nigeria, out of 196 samples that were collected, AFs were detected in 97 samples (AFs levels ranged between 24 and 1,164 μg/kg), OTA in 56 samples (20 and 1,642 μg/kg), and ZEA in 93 samples

(24 and 1,169 μg/kg; Hussaini et al., 2009a). Later, Iqbal et al. (2016) investigated that out of 62 samples analysed in Pakistan, 37% of the samples contained OTA in the range of 0.6 to 25.4 μg/kg and AFB1 in the range of 0.04 to 21.3 μg/kg. Likewise, Majeed et al. (2013) also found contamination of 50% of rice samples examined with OTA (0.06 to 15 μg/kg) and AFs (0.05 to 24 μg/kg). Other studies have found multiple mycotoxins in Turkish, Nigerian, Indian, and Chinese rice (Reddy et al., 2009b; Aydin et al., 2011; Makun et al., 2011). For examples, Makun et al. (2011) found that 14% of the samples were positive for FB1 with a level of mean concentration 0.2 μg/kg. A study conducted by Majeed et al. (2018) reported 23 mycotoxins in 180 rice samples with AFs, FBs, and ZEA were prevalent toxins reported in 20–56% of the samples, whereas OTA, HT-2 toxins and DON were reported in few samples. The concentration of these toxins was ranged in between 0.61 and 22.98 μg/kg.

Maize (*Zea mays* L.)

In pre-and post-harvest conditions, corn is commonly colonized by spoilage fungi, whose relative abundance depends on both biotic and abiotic stresses that affect the mycotoxin production rate. ZEA, FBs and TCT were the most prevalent mycotoxins contaminating maize in Mediterranean countries (Jestoi, 2008), whereas AFs were common in tropical and subtropical regions (Muriuki and Siboe, 1995). Maize samples from the Mediterranean basin have been reported to contain different types of mycotoxins including FBs and AFs (Marin et al., 2012). A study conducted in Italy over 1995–1999 revealed that two maize samples had AFs levels of as much as 109 to 158 μg AFB1/kg, with the mean range of 0.3 to 4.10 μg AFB1/kg seeds (Pietri et al., 2004). Samples from Turkey also showed high levels of AFs in the range of 120.3 to 133 μg/kg (Giray et al., 2009). Besides, a study conducted in Syria reported AFs levels >20 μg/kg (Majid, 2007).

Maize sold in West Africa also had high levels of AFs contamination, ranging from 0.4to 490 μg/g in Ghana, 0.2 to 120 μg/g in Benin, and 0.7 to 110 μg/g in Togo (James et al., 2007). Four out of every five maize samples from the Southern Guinea Savanna exceeded the AFs level of 20 μg/g recommended by international authorities. Out of 190 maize samples that were analysed for contamination of multiple mycotoxins in India, 69 (34.8%) samples were contaminated majorly with AFs (Janardhana et al., 1999). There was also a high level of AFs detected in stored maize grains (43%), and most of the contaminated samples had levels greater than 20 μg/kg. The samples from Egypt included 30 μg/kg of TAFs (Abdelhamid, 1990), from Southern Guinea contained 77 μg/kg (Hell et al., 2003), and the samples collected in Croatia had AFB1 ranged between 224 and 614 μg/kg levels during 1996 to 1997 (Jurjevic et al., 2002). However, Croatia had the highest percentage of OTA positive samples (25%) with more OTA concentration, i.e., 31.7 μg/kg (Segvic et al., 2009).

The FBs synthesized by *Fusarium* are the most common contaminants, with contamination incidence often near 100% despite the presence of these two mycotoxins. FBs were found in 100% of maize samples grown in Turkey, with a mean level of 8,240 μg/kg of toxin production (Oruc et al., 2006). It has been found that 54 French maize samples imported into the UK between 2004 and 2007 contained higher than 10 μg/kg levels of FBs contamination (Scudamore and Satel, 2009). According to a study of Pietri et al. (2004), samples contaminated with *Fusarium*-derived ZEA over 200 μg/kg increased to 53.8%, with a mean contamination of 453 μg/kg and a sample showed much higher level, i.e., 2,531 μg/kg ZEA. The dominant mycoflora of 12 maize samples collected from affected households were *Fusarium*, which produced FB1 at levels between 0.25 and 64.7 mg/kg (Bhatt et al., 1997). Additionally, FB1 was detected in 25 rain-affected maize samples in the range of 00.04 to 65 mg/kg and 89% of normal maize samples contained AFB1 in the range of 0.38 to 109 μg/kg. In Albania, Topi et al. (2021) analysed 45 maize samples and found that 78% of the samples were majorly contaminated with FB1 and FB2 with concentration ranging from 59.9 to 16,970 μg/kg. They also found that 31% of the maize samples exceeded the EU maximum permitted level of FBs, i.e., 4,000 μg/kg.

Wheat (*Triticum aesticum* L.)

During transport and storage, wheat is also affected by a wide species of fungi. Fusarenon X-glucoside (FUXGlc), a *Fusarium* mycotoxin reported for the first time in wheat grains induced by *Fusarium* species (Nakagawa et al., 2011). They also reported the levels of OTA and DON were, respectively, 12 and 53 μg/kg in wheat. The T-2 and AFB1 toxins were also detected in wheat flour by Badiale-Furlong et al. (2003). An additional study found that FB1 levels ranged from 0.5 to 3.9 μg/kg of wheat and between 0.6 and 2.3 μg/kg of flour (Birck et al., 2003). There were 74% (24.91%) of wheat samples contaminated with DON from the southern region, and levels of toxins ranged from 603.2 to 850.4 μg/kg (Mallmann et al., 2003). Sulyok et al. (2006) determined the detection limits of DON in wheat samples which ranged from 0.03 to 220 μg/kg. It was reported that *Fusarium* species, particularly *F. gramanearum* on wheat kernels in five Kenyan districts produced ZEA and DON (Muthomi and Mutitu, 2003).

It has been shown that samples of wheat and wheat flour purchased from resident Egyptian markets contain *Fusarium* mycotoxins (Aziz et al., 1997). In five wheat samples, DON was detected at levels from 103 to 287 μg/kg, and in one flour sample and one bread sample, DON was detected at 188 and 170 μg/kg, respectively. A total of 10 wheat samples were found to contain 28 to 42 μg/kg range of ZEN levels and four samples of bread and flour contained 95 μg/kg and 34 μg/kg, respectively. There are certain *Fusarium* species like *F. graminearum*, *F. avenaceum*, and *F. culmorum* that are predominant in *Fusarium* head blight infected wheat and produce mycotoxin (Bottalico and Perrone, 2002). Besides, 41 wheat samples harvested and consumed in few regions of Turkey showed contamination of *Aspergillus* and *A. parasiticus* as well as production of AFs including B1, B2, G1, and G2 in the range of 10.6 to 643.5 μg/kg (Giray et al., 2007). In total, 59% of the samples were positive for TAFs, such as B1, B2, G1, and G2 with respective percent of 42, 12, 37, and 12%. Besides, some emerging mycotoxins have also been reported in wheat samples. For instance, *F. tricinctum* was found to be produced various ENNs such as ENN A, A1, B, and B1 in durum wheat ($n = 260$; at levels 55 to 596 μg/kg) and wheat ($n = 470$; at levels 47 to 142 μg/kg; Orlando et al., 2019). More recently, Topi et al. (2021) found that 23% of the wheat samples ($n = 71$) were found to be often contaminated with *Fusarium* toxin, i.e., DON. In their study, the EU maximum permitted level (1,250 μg/kg) was exceeded on one wheat sample which showed 1916 μg/kg DON concentration.

Other small cereal food crops

In certain conditions, other cereals like barley (*Hordeum vulgare* L.), sorghum (*Sorghum vulgare* L.), oats (*Avena sativa* L.), and millets (*Pennisetum glaucum* L.) are also found to be associated with mycotoxigenic fungi during transportation, storage, and even at the field. There is evidence that these grains serve as a suitable substrate for the development of AFs. Eighty-four (72%) of the 116 samples of oat and barley collected from eastern Canada were associated with DON with levels ranged 8 to 9 mg/kg (Campbell et al., 2000). There were 34% of 73 oat samples that contained DON, and 34% of the 53 barley samples, and 15% of the 26 oat samples that contained nivalenol. Samples of barley contaminated with DON had a maximum level of 15.8 mg/kg (Abramson et al., 1998). The concentration of FB1 in sorghum ranged from 0.14 to 7.8 μg/kg (Bhatt et al., 1997). In another study, FB1 (0.07–8 μg/kg) was found to occur naturally in Indian sorghum along with AFB1 (5 to 125 μg/kg) (Shetty and Bhatt, 1997). Besides, ZEA was also found in grains with moisture contents of 20–22% (Jurjevic et al., 2007). In Nigeria, Hussaini et al. (2009b) reported AFs in several sorghum samples. It was also reported that 92 μg/kg of moniliformin and 414.6 μg/kg of beauvericin were found in pearl millet collected from few regions of Africa and Asia (Wilson et al., 2006). Orlando et al. (2019) analysed 282 spring barley, 172 tricale and 56 winter barley samples from the French harvest of 2012 to 2014 and found that samples were associated with *F. avenaceum* and *F. Poae.* The ENNs contents produced by both *Fusarium* species varied between years but were constantly highest on triticale (levels 131 to 1,218 μg/kg) and spring barley (levels 199 to 1,316 μg/kg). Polišenská et al. (2020) also found frequent occurrence of ENNs, beauvericin, and nivalenol in hulless barley and HT-2 and T-2 toxins, beauvericin and ENNB in hulless oats which significantly reduced the quality of oats and barley and caused health risk. The DON and ZEA contents in barley (DON: 1250 μg/kg, ZEA: 100 μg/kg) and oats (DON: 1750 μg/kg, ZEA: 100 μg/kg) were far from being exceeded the limit fixed by EU [Regulation 1881/2006; European Commission (EU), 2006]. Likewise, Edwards (2007) reported another mycotoxin, i.e., DON in barley (1,416 μg/kg) and oat 282 (μg/kg) samples. Correspondingly, Schöneberg et al. (2016) found that frequency of occurrence of DON was higher in barley (57%) compared to oats (45%) with a much higher level of DON in barley (4,860 μg/kg) compared to oats (1,328 μg/kg). However, researchers have found lower content of ZEA (<10 μg/kg) in barley (Gil-Serna et al., 2013) and oat (Schöneberg et al., 2016).

Pulses and oilseeds crops

Pulses provide dietary protein and other essential nutrients. However, improper storage and handling can lead to mycotoxins contamination. It has been reported that *Aspergillus* species produced 333 to 10,416 μg/kg of AFB1 in pulses and oilseeds crops (Begum and Samajpati, 2000). In Ontario, Canada, Tseng and Tu (1997) investigated the presence of FB1 in adzuki bean (*Vigna angularis*) and green gram (*Vigna radiata*) samples but not in the healthy samples. By HPLC, it was determined that the adzuki and mungbean samples contained respective 261 and 230 μg/g of FB1. Thus, a future study of mycotoxin contamination of various foods including legumes needs to be undertaken. The results of another study showed that out of 66 isolates of *A. flavus* from mustard seeds, 24 produced AFs (0.25 to 22 μg/ml), with eight isolates producing extremely high levels of AFs and the remaining 16 isolates producing very low amounts of AFs.

Mycotoxins are not produced by all fungi that infect food crops. In this regard, Ahmad and Sinha (2002) found that out of 34 isolates of *F. moniliforme,* only 13 isolates were able to produce ZEA (range 1.2 to 4.0 μg/ml) and of 12 isolates of *P. citrinum*, only four produced CT at levels ranging from 1.0 to 3.0 μg/ml (Ahmad and Sinha, 2002). South Africa's cowpea cultivars contained 0.12 and 0.61 μg/g FB1, while cultivars from Benin were free of FBs (Kritzinger et al., 2002). A total FB concentration of 0.8 to 25.30 μg/g was determined in the pulses, and the highest level of FB1 was detected at 16.86 μg/g (Kritzinger et al., 2002). Two types of fungi, *A. parasiticus* isolated from beans seeds and *F. moniliforme* isolated from soybeans, produced significant concentrations of AFs (196.58 μg/kg) and FBs (198 mg/kg), respectively, as demonstrated by Embaby et al. (2013). In a recent study, 81 cowpea samples analysed in Nigeria were positive for AFs with concentrations ranged between 84 and 209 μg/kg (Afolabi et al., 2019). In addition, beauvericin was also detected in few samples.

Peanut (*Arachis hypogaea* L.)

Peanuts are considered the second most important legume worldwide after beans. Unfortunately, lack of storage technologies causes mycotoxins, especially AFs, to be released (Kaaya et al., 2006). Researchers have discovered AFs types B and G as well as cyclopiazonic acid (CPA) in peanuts grown in Argentina (Formosa province) by *A. flavus* (Pildain et al., 2004). There were 10 to 346 μg/kg of AFs in peanut cake samples, and OTA was below the limit of quantification (2 μg/kg) (Ediage et al., 2011). Researchers from Córdoba, Argentina, reported the presence of black species of *Aspergillus* in peanuts that produce OTA. A 0.5 μg/kg to 170 μg/g range of OTA was found in 32% of the seed samples analysed by Magnoli et al. (2006). OTA-producing isolates were found in 43 of 47 *Aspergillus* section *Nigri* isolates (27%) studied and overall, *A. carbonarius* presented in higher amounts (57%) as OTA producing fungi (Magnoli et al., 2006). As a result of a subsequent study, they discovered that 104 (32) of 322 isolates of *Aspergillus* section *Nigri* produce OTA, and that the quantities were between 2 μg/kg and 24 μg/ml (Magnoli et al., 2007).

Several peanut samples from India were found to contain levels of AFs >30 μg/kg in the study of Kishore et al. (2002). A disquieting AF amount of 852 μg/kg and ZEA of 98.1 to 847.3 μg/g were found in samples analysed in India. There was also evidence of mycotoxins in Brazilian groundnut seeds from sowing to harvest. In this context, Gonçalez et al. (2008) found that the levels of AFs (4.20 to 198.8 μg/kg) and CPA (260 to 600 μg/kg) were higher in 32% of peanut samples studied. The most common toxic compounds are those produced by *Aspergillus* species. In terms of mycotoxins considered by regulations, AFs exceeded the USDA maximum limit of 20 μg/kg in 90% of samples studied by Ezekiel et al. (2012). Similarly, groundnuts from Ethiopia had AF levels that ranged from 15 μg/kg to 11,900 μg/kg (Chala et al., 2013). In Nigeria, the content of TAFs in groundnut cakes, roasted groundnut, and boiled groundnut were respective 11.15, 4.50, and 1.51 μg/kg, suggesting that groundnut cake had the highest incidence and concentrations of TAFs (Adefolalu et al., 2021). They also found that contents of AFs increased with prolonged storage time.

Fruits and fruit juices

During and after harvest, raw and processed horticulture products may contain mycotoxins. In addition to cereals, fruits and fruit juice may also pose a potential risk to toxin contamination. *Aspergillus* and *Penicillium* are two of the most recognized species worldwide that produce toxins in fruits. The dried fruits of vines (e.g., raisins, sultanas) contain higher OTA levels worldwide (Palumbo et al., 2011). According to reports, grapes contain potential amounts of AFs (0.3%), OTA (6.0%), PT (0.5%), and TCT (1.2%; Serra et al., 2005). Sixty samples of retail dried vine fruits collected from the United Kingdom revealed presence of OTA and AFs above 53.7 μg/kg (MacDonald et al., 1999). The majority of the reports indicated that most contaminated samples had an OTA level over 2 μg/kg, with maximum values exceeding 100 μg/kg (Magnoli et al., 2004; Aksoy et al., 2007). Chulze et al. (2006) found higher OTA levels in grape juice than allowed, i.e., <10 μg/kg (Chulze et al., 2006). In pear inoculated with fungus *P. expansum*, PAT was found to form and to diffuse in the apparently sound flesh, in a concentration exceeding the accepted European limits (50 μg/kg; Laidou et al., 2001). The occurrence of PAT (up to 80.5 mg/kg) was recorded in 89 percent of 351 rotten apple samples collected throughout Portugal, and *A. carbonarius* and *T. roseum* produced OTA and TCT in grapes before harvest time (Martins et al., 2002). Likewise, Mogensen et al. (2010) also found contamination of grapes with FB2 (171–7,841 μg) and FB4 (14–1,157 μg) produced by *A. niger* strains.

Besides, Jimenez and Mateo (1997) reported the occurrence of FB1, ZEA, DON, TCTs, T-2 and HT-2 toxins. In another study conducted in Egypt, OTA was present in all fig samples (60 to 20 μg/kg), apricot samples (50 μg/kg to 110 μg/kg), and plum samples (210 to 280 μg/kg) (Zohri and Abdel-Gawad, 1993). However, no sample was found to exceed the safe level of 50 μg PT/I. Based on the findings of Beretta et al. (2000), apple derivatives tend to represent a PT intake below the tolerable level of 0.4 μg/kg bw/day. The different apples tested by Tangni et al. (2003) showed PT at 79, 86, and 43%. A study conducted by Hussain et al. (2020) found more PT content in mango (110.9 μg/kg) than that of orange (6.3 μg/kg). The study also revealed that PT content was higher in mango fruits than in processed products like juice, jam, and pulp.

Besides, out of 70 mango fruits and 77 orange-based products analysed for occurrence of mycotoxins, they found that 29 mango samples (21.8%) and one orange sample (0.7%) exceeded regulatory limit (50 μg/kg) of PT in Pakistan. These observations are also in accordance with the study conducted by Iqbal et al. (2018) who found high level of PT contents in fruits and fruit juice with a maximum of 1,100 μg/kg in a red globe grapes sample. The higher PT content in apple juice was also reported in USA (2,700 μg/kg, Harris et al., 2009), Tunisia (889 μg/kg, Zouaoui et al., 2015), Turkey (1,416 μg/kg, Icli, 2019), and India (845 μg/kg, Saxena et al., 2008). On the contrary, in Argentina Oteiza et al. (2017) also found lower level of PT content in mango samples (6,415 μg/kg) than that of fruit juice samples (7,339 to 19,662 μg/kg). Studies conducted in Malaysia also did not find PAT in mango juice (Abu-Bakar et al., 2014; Lee et al., 2014). Apple juice analysed from Saudi Arabia attained PT levels in the range of 5 to 50 μg/kg (Al-Hazmi, 2010). Likewise, lower PT contents were reported in various fruits juice (apple, orange, grapes) analysed in Greece (10.54–5.57 μg/kg, Moukas et al., 2008) and South Korea (30.9 μg/kg, Cho et al., 2010).

Decontamination strategies of mycotoxins in food commodities

In recent years, decontamination of mycotoxins in food commodities became crucial due to their toxic effects on people and animal health. Worldwide, numerous chemicals, physical, botanical, and biological strategies for detoxifying mycotoxins from contaminated foodstuffs have been explored (Table 5). However, among the many methods established, only a limited number of decontamination techniques found a practical application are reviewed below. The ideal characteristics of mycotoxins' detoxification processes applied to food are summarized in Figures 1, 2. Novel technologies include the use of essential oils, natural extracts, irradiation, ozone treatment, pulsed light, cold plasma, and microbiological methods.

Chemical methods of decontamination of mycotoxins

The best approach to avoid contamination of food commodities by mycotoxins is to prevent this contamination rather than using detoxification or decontamination procedures. In order to prevent contamination, proper agricultural practices are required. However, in many cases fungal growth cannot be avoided as consequently leads to the formation of mycotoxins. Two of the conventional techniques to reduce mycotoxins levels are cleaning and milling or dehulling. Milling or dehulling is particularly applied to cereal grains and allows to remove the outer layer of the grains, which concentrated the higher mycotoxins level. Although these strategies allow to reduce contamination, if the contamination affects the milled grains, it cannot be controlled just with the milling process. The mechanism of detoxification of AFB1 by citric acid leads to the formation of the beta-keto acid structure, catalysed by an acid, followed by hydrolysis of the lactone ring with formation of AFD1, which has lower mutagenic activity (Mendez-Albores et al., 2005). The use of lactic acid also results into the conversion of AFB1 into AFD1.

Other methods include the use of chemicals such as hydrogen peroxide and ozonated water, and propionic acid. The ozone treatment is effective in the elimination of mycotoxins and it does not leave toxic residues. Besides, it is environmentally friendly and minimally affects the quality of foods. However, it can originate the oxidation of lipids, degradation of bioactive compounds and it has high costs associated (Mir et al., 2021). A study carried out by Trombete et al. (2017) applied ozone at a concentration of 60 mg/L for 300 min in wheat and allowed to reduce DON and AFs at a reduction rate of 64 and 48%, respectively. Savi et al. (2014, 2015) applied ozone gas at a concentration of 60 μmol/mol for 180 min to wheat samples and could effectively reduce mycotoxins contamination: 94.6% reduction rate in the case of AFB1, 84.5% for AFB2, 80% for AFG1, 81% for AFG2 and 100% for DON. However, these chemical methods present the drawback

TABLE 5 Mycotoxins decontamination approaches in food commodities, their advantages, and disadvantages.*

	Physical decontamination	Chemical decontamination	Biological decontamination
Examples	Sieve cleaning	Hydrochloric acid	Beneficial microbes
	Sorting	Organic acid	Plant extracts
	Washing	Ammonium hydroxide	Essential oils
	De-hulling	Formaldehyde	
	Steam heating	Ozone	
	Infrared heating	Sodium bisulphite	
	Microwave heating	Chlorinating agents	
	Irradiation		
	Cold plasma		
	Photocatalytic detoxification		
Advantages	Efficient against specific type of mycotoxins	Efficient against specific type of mycotoxins	Efficient against specific type of mycotoxins
	Low changes in food organoleptic properties	Higher efficiency rate	Cost effective
	Does not comprise chemicals usage	Applicable at larger scale	Eco-friendly
			Does not include chemicals usage
Disadvantages	Unfeasible	Health risk	Time consuming
	Might be limited to larger scale industries with sophisticated equipment	Formation of toxic byproducts and not environmentally friendly	Non practical, i.e., more effective in controlled conditions
	Time consuming and expensive	Enhancing bioavailability of masked mycotoxins	Not easily available
	Possible changes in color and food quality in case of thermal treatment	Time consuming	Sometime causes alternation in taste

*Source: Mendez-Albores et al. (2005), Mir et al. (2021), Mravlje et al. (2021).

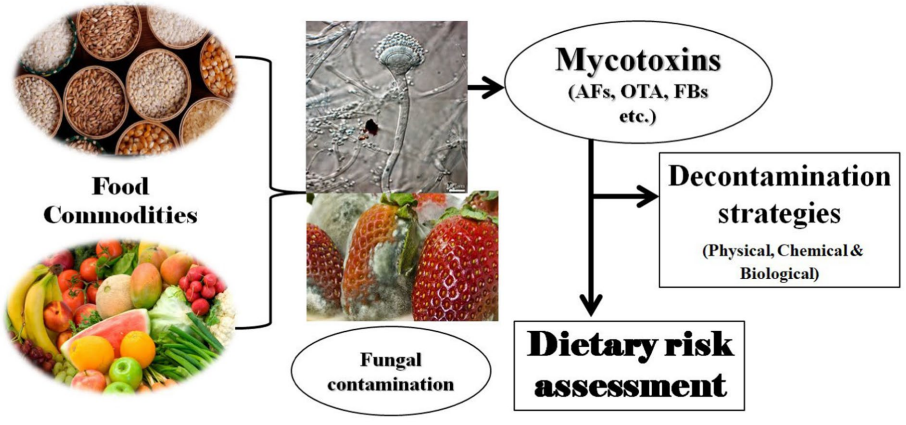

FIGURE 1
Image showing major types of mycotoxins in food commodities and their various decontamination strategies.

of leaving residues in foods and some have still limited effect, therefore the need for newer decontamination methods has boosted novel technologies. Additionally, their effectiveness is not broad spectrum and depends on the dose and target mycotoxigenic fungal isolates, and results have been found inconsistent when applied in the field/ or industry. Besides, more *in vivo* studies are required on the activity, bioavailability, and toxicity.

Physical approaches of decontamination of mycotoxins

Irradiation

One of the technologies used to decontaminate food commodities from mycotoxins is irradiation, which uses ionizing energy. Irradiation

FIGURE 2
Ideal characteristics of mycotoxins' detoxification processes applied to food commodities.

is effective and a non-thermal method, however, can originate lipids or vitamins oxidation, off-flavors or changes in foods' color (Mir et al., 2021). Gamma irradiation has been applied to different cereals (e.g., maize, wheat, barley, rice) to reduce mainly AFB1 (Aziz et al., 2004; Aquino et al., 2005; Mohamed et al., 2015) but also AFB2 (Aquino et al., 2005), ZEA (Aziz et al., 2004), OTA (Aziz et al., 2004), and FB1 (Aziz et al., 2007) in doses ranging from 0.5 to 10 kGy. The degradation of mycotoxins depends on the dose of gamma irradiation, but also on the moisture level of samples. Mehrez et al. (2016) reported that the degradation of mycotoxins in a cereals sample irradiated with 8 kGy and having a moisture content of 16% was significantly higher than when the sample have a moisture content of 11%. However, sometimes it may not kill all targeted mycotoxin-producing fungi. The environment where objects are being irradiated can be very harmful – standing there could lead to injury and mutation of people's cells (Mir et al., 2021).

Pulsed light treatment

The pulsed light technology is innovative and promising. Moreover, it does not leave residues in food commodities, and it is cost-effective, but only decontaminates the foods surface and reduces the germination of seeds (Mir et al., 2021). This treatment is influenced by factors related with food (type of food matrix, thickness, composition), mycotoxins (type of mycotoxins) and pulse light (power of pulses, number of pulses, distance between lamp and light). Wang B. et al. (2016) has reported a reduction of 75% of AFB1 and 39% AFB2 in rice treated with 0.52 J/cm^2/pulse for 80s. Moreover, Chen et al. (2019) reported a reduction of 35.5% of DON in barley treated with 180 pulses for 60s. Pulsed light has also been used in combination with citric acid to degrade AFs in peanuts (groundnuts; Abuagela et al., 2019). The technology has a low penetration power, which is one of its main disadvantages. It is therefore initially proposed to use pulse light technology for surface decontamination of solid food commodities, unpackaged or packaged in UV-transparent materials. It is crucial to consider food surface topography in these applications.

Cold plasma

Cold plasma is a novel and non-thermal technology in which reactive species (e.g., O, O_3, OH, NO, NO_2) generated by cold plasma degrade mycotoxins and convert them in other less toxic compounds. This procedure presents several advantages such as the maintenance of the quality of foods (Mir et al., 2021). Wielogorska et al. (2019a) reduced 65% of AFB1 and 64% FB1 in maize after application of cold plasma (10 min, 20 Hz). According to Mravlje et al. (2021), the frequency of *Alternaria* and *Epicoccum* fungi (in common and tartarian buckwheat, respectively) were significantly reduced after treatment with cold plasma for 90 and 120 s. One study found a twenty-minute direct high voltage atmospheric cold plasma treatment of 100 µg of DON in 1 ml of aqueous suspension reduced DON structure by more than 99% and improved Caco-2 cell viability by over 80%. The same treatment on 100 µg of powdered DON toxin, however, only reduced DON levels by 33% and resulted in a 15% increase in cell viability (Ott et al., 2021). A study by Chen et al. (2022) showed that after 8 min of exposure at 50 kV in air atmosphere, 83.99% of the DON solid standard was degraded in wheat samples. After degradation, there were no noticeable effects on wheat quality other than a slight decrease in the whiteness of wheat powder. Therefore, cold plasma may be a promising strategy for mycotoxins decontaminant in food commodities. These technologies, however, have several limitations, such as lipid oxidation, protein oxidation, food discoloration, and changes in organoleptic properties, which limit their application in food industries (Olatunde et al., 2021).

Biological methods of detoxification of mycotoxins

Biological methods are environmentally friendly and do not leave toxic residues, but it is difficult to select nontoxigenic bio-competitive microorganisms and they require longer period of time for the detoxification (Mir et al., 2021).

Use of beneficial microbes

Different microbials (e.g., bacteria, moulds, yeasts) and enzymes can be used to inactivate or degrade mycotoxins, allowing obtaining fewer toxic compounds. Some of the microorganisms that have already been used to decontaminate foods include lactic acid bacteria, *Bacillus licheniforms*, *B. subtilis*, and *Saccharomyces cerevisiae*. The microorganisms used for mycotoxin detoxification processes can be applied at any stage (pre or postharvest) and must show to be efficient and cost effective. Ansari et al. (2015) has used kefir-grains to reduce the contamination of pistachio with AFB1 in 96.8% while Farzaneh et al. (2012) used *Bacillus subtilis* UTBSP1 to obtain the reduction of AFB1 in the same matrix with an effectiveness of 95%. However, further investigations are needed to determine the safety and mechanisms of beneficial microbes against mycotoxin-producing fungi.

Use of botanicals

Mycoflora incursion on agriculturally important food commodities has been managed with several synthetic fungicides. To date, physical and chemical methods to reduce or remove mycotoxins from food have not proven to be satisfactory or useful. These toxins have negative effects on the food chain and can thus be eliminated with botanical-based detoxification (Gurney et al., 2014). In addition to the controversy surrounding synthetic preservatives, users have become more interested in natural food protection for improving the food quality and shelf life and protecting them from biodegradation by mycotoxigenic microbes (Pandey et al., 2016). In the academic and industrial communities, aromatic and medicinal plants are being studied for their antifungal effects against mycotoxigenic fungi, because of their eco-friendly and safety concern. Natural extracts are constituted of bioactive compounds (e.g., phenolics, alkaloids, terpenes) with anti-mycotoxigenic activity. Sultana et al. (2015) reported that the extract from neem leaves allowed reducing the contamination of cereals by AFs during storage. However, this extract presented a strong aroma which restricted its use. Ponzilacqua et al. (2019) reported the *in vitro* mycotoxins decontamination effect of Brazilian medicinal herbs extracts. These authors reported a time dependent AFB1 reduction by araçá, sweet passion fruit, oregano, and rosemary but no degradation on OTA or ZEA by any of the tested extracts were reported. The highest AFB1 reduction (approximately 60%) was found for rosemary extract after 48 h, followed by araçá and oregano extracts. Iram et al. (2016) compared the capacity of *Cassia fistula* and *Ocimum basilicum* aqueous extracts to decontaminate pistachio by AFB1 and AFB2. These authors reported that *O. basilicum* leaves extract was able to degrade 90.4% of AFB1 and 88.6% of AFB2, while the extracts of *O. basilicum* twigs, *C. fistula* leaves and twig were less efficient. Due to the search for more "natural" additives and agents, natural extracts from different parts of the plants (e.g., leaves, fruits, roots), are very promising for mycotoxins decontamination of foods. However natural extracts present high variability in their composition due to the influence of factors such as the selected cultivar, part of the plant used and edaphoclimatic conditions (Mateus et al., 2021). Therefore, there is the need of establishing guidelines for the standardization of these extracts in order to better control their effectiveness, in particular as anti-mycotoxigenic agents.

In addition, EO-based detoxification represents a promising substitute to eliminate mycotoxins and improve food and feed quality. Essential oils are produced by secondary metabolism of higher plants and are complex mixtures of volatile organic molecules. Hydro-distillation, low-pressure distillation, and high-pressure distillation are all methods of obtaining these essential oils. Essential oils are composed largely of terpenes and terpenoids followed by aromatic and aliphatic compounds. There are numerous structural variations of terpenes, which include monoterpenes, sesquiterpenes, diterpenes, hemiterpenes, triterpenes, and tetraterpenes. In this article, EOs that have been used against mycotoxigenic fungi or to reduce mycotoxin levels including AFs, ZEA, OTA, and FBs in food products are discussed.

EOs for detoxification of AFs

Many researchers have suggested the use of EOs to reduce the growth of fungi and against the production of AFs by *A. flavus* and *A. parasiticus* (Maraqa et al., 2007; El-Nagerabi et al., 2012). Many food-borne fungi produce AFs that are inhibited by EOs and flavonoids (Alpsoy, 2010). *Azadirachta indica* seeds extract completely inhibited AFs production level in maize at concentrations of 500 and 1,000 mg/kg, while *Morinda lucida* seeds extract inhibited AFs production level at 1000 mg/kg concentration (Bankole, 1997). Iranian medicinal plant derived EOs also act as novel antioxidants and AFs inhibitors in food systems. As an example, *Satureja hortensis* and its active ingredients were found to act as effective inhibitors of AFs produced by *A. parasiticus*. The IC_{50} values for carvacrol and thymol for AFB1 and AFG1 were 0.50 and 0.06 mM, respectively. Carvacrol and thymol were found to be the potent constituents of *S. hortensis* and they may be used to reduce AFs contamination in food commodities (Razzaghi-Abyaneh et al., 2007). The EOs from *Adansonia* species has also inhibited the levels of TAFs and AFB1 secretion by *A. flavus* (47.2 to 95.7%; 28.1 to 89.7%) and *A. parasiticus* (42.7 to 93.3%; 25.9 to 80.2%; El-Nagerabi et al., 2013). NKD-208 isolates of AF-producing *A. flavus* were strongly inhibited by the *Callistemon lanceolatus* EO (Shukla et al., 2012). The EO of *Zataria multiflora* at 150 mg/kg reduced AFs production level up to 99.4% (Gandomi et al., 2009). Similarly, El-Nagerabi et al. (2012) also found that *Nigella sativa* EO caused potential reduction of AFB1 level by inhibiting the growth of *A. flavus* and *A. parasiticus*. Another EO, i.e., *Ageratum conyzoides* EO was found to inhibit AFs production level at 2.0 µl/ml produced by *A. parasiticus* (Ab2242) and at 1.5 µl/ml by *A. flavus* (La3228; Adjou et al., 2012). Marjoram and clary sage EOs significantly reduce the growth of *A. parasiticus* (Gomori et al., 2013). The 10 µl dose of *A. conyzoides* EO was more effective than *Origanum*

vulgare in inhibition of AFs in soybeans (Esper et al., 2014). EOs derived from *Cymbopogon martini, Foeniculum vulgare*, and *Trachyspermum ammi* were also found to reduce various types of toxin production by *A. niger* and *A. flavus* at respective dose of 0.5 and 0.75 µl/ml (Gemeda et al., 2014). Similarly, EOs from *Artemisia nilagirica* (Sonker et al., 2014b) and *Cymbopogon citratus* (Sonker et al., 2014a) were found to inhibit AFs and OTA production levels in grapes at respective dosage 0.8 µl/ml and 1.6 µl/ml. Similar dose of EO from *L. alba* has been found to control AFB1 production level in green gram (Pandey et al., 2016). Likewise, in various food commodities, the level of AFs inhibition has been reported due to *Rosmarinus officinalis* and *Trachyspermum copticum* (450 mg/kg) EOs by Rasooli et al. (2008), *Thymus eriocalyx* and *TX-porlock* EOs (250 mg/kg) by Rasooli and Owlia (2005), oil derived from Turmeric leaves (95.3 and 100% inhibition) by Sindhu et al. (2011), and *Ocimum gratissimum* EO by Prakash et al. (2011).

EOs for detoxification of ZEA

The search of literature revealed that little work has been done on efficiency of EOs on reduction of ZEA levels in food commodities. EOs of palmarosa, cinnamon, clove, lemongrass, and oregano have been found effective in reduction of ZEA and DON levels. ZEA was found to be produced by *F. graminearum* in naturally contaminated maize grains, while in control sets levels of both toxins determined >500 mg/kg (Marin et al., 2004). Likewise, another study also found that clove and palmarosa EOs proved as better grains' protector for maize grains as both EOs reduced ZEA and DON production levels as well as growth rate of *F. graminearum* under variable environmental conditions (Velluti et al., 2004).

EOs for detoxification of FBs

EOs are also found potential in detoxification of FBs. Researchers have found that EOs from cinnamon, lemongrass, palmarose, clove, and oregano inhibited FB1 production level in maize grains (Velluti et al., 2003). Lopez et al. (2004) evaluated *Aloysiatriphylla*, *A. polystachya*, *Origanum vulgare,* and *Mentha piperita* EOs and found that among these EOs, *O. vulgare* EO significantly reduced FB1 level produced by *F. verticillioides,* whereas EO from *A. triphyla* was found to increase the mycotoxin levels at lower doses. Relatively, both *O. vulgare* and *A. triphylla* EOs at 250 and 500 µl/ml had efficient efficacy against FB-producing *F. verticillioides* (Lopez et al., 2004). In another study, cinnamon oil was also found to inhibit FB production and mycelia growth of *F. culmorum* and *F. graminearum* at 500 µg/g doses (Hope et al., 2005). Besides, the EO of *Zingiber officinale* had the inhibitory effect on FB1 and FB2 production at respective doses 4,000 and 2,000 µg/ml (Yamamoto-Ribeiro et al., 2013).

In the study of Xing et al. (2014), the EOs from *Litsea cubeba*, cinnamon, spearmint, citral, anise, clove, camphor, and eucalyptus inhibited levels of FB1 alongwith *F. proliferatum* growth. Among these EOs, they reported cinnamon as a most effective EO followed by citral, eugenol, eucalyptus, anise and camphor. As Cinnamon EO was found most potential, it reduced FB1 level from 15.03 to 0.89 µg/ml at a concentration of 280 µg/ml. In addition to EOs, their active constituents have also been found potential in reduction of mycotoxin level. For example, menthol, limonene, thymol, and menthone with thymol was the most active in reduction of FB1 level and its biosynthesis by *F. Verticillioides* at 75 mg/kg (Dambolena et al., 2008).

EOs for detoxification of OTAs

From time-to-time investigations were carried out to control OTAs contamination and related fungi using plant EOs. Both oregano and mint EOs were able to inhibit OTA production levels by *A. ochraceus* (Basílico and Basílico, 1999; Soliman and Badeaa, 2002). The EOs from Clove leaf, bay leaf, and cinnamon at 50 ppm caused reduction of OTA levels in wheat substrate and a complete inhibition of this toxin was found at 500 ppm doses (Cairns and Magan, 2003). Murthy et al. (2009) found that the EO from *Plectranthus amboinicus* was completely reduced OTA levels in foods as well as toxigenic strains of *A. ochraceus* at 500 mg/kg. Furthermore, the use of 100 mg/kg of this EOs in food samples such as maize, groundnut, and poultry feed inhibited the growth of *A. ochraceus* (Murthy et al., 2009). The EO from *A. framomumdanielli* also possessed ochratoxigenic activity in cocoa bean as it decreased OTA contents from 500 to 2,000 mg/kg (Aroyeun et al., 2009). Likewise, 0.10% of basil EOs reduced OTA production level from 135 to 98 µg/ml in study of Mohamed et al. (2012). Besides, EOs from both *Artemisia nilagirica* (Sonker et al., 2014b) and *Cymbopogon citratus* (Sonker et al., 2014a) were found to be completely reduced the levels of OTA in table grapes at respective doses 0.8 and 1.6 µl/ml.

The examples given here are just a few out of the many EOs that have been used to reduce mycotoxin contamination in food commodities, many of which cannot be covered in this short review. Thus, these EOs can be used for the detoxification and reduction of AFs, FBs, ZEA, and OTA levels as well as related fungi in food commodities. Food commodities can be protected from microbial contamination by encapsulating these potential EOs either as nanoemulsions or nanoparticles or packaging films. Furthermore, encapsulation enhances the oxidative stability, thermostability, shelf life, and biological activity of EOs. Additionally, it can be helpful in controlling the volatility and release properties of essential oils. However, more *in vivo* studies are required on the efficacy at larger scale storage conditions, bioavailability, and toxicity. Further studies are also needed to determine the safety and mechanisms of these EOs depending on mycotoxin-producing fungi as well as their potential health concern.

Conclusions and perspectives

Increasing population requires the need to stockpile bulky foodstuffs for use in near future. But improper storage of such foodstuffs leads to the colonization by mycotoxigenic fungi. This results in contamination of food commodities by multiple mycotoxins, and this is a global concern. In this review, we describe mycotoxins in various food commodities, including their prevalence, toxicity, regulation, and detoxification. Mycotoxin detoxification in foods is a significant challenge due to the complexity of few food matrixes like fruit juice, edible oils and the relatively low content of mycotoxin. Researchers worldwide have used a variety of detection methods with

varying levels of sensitivity. Sample preparation techniques, mycotoxin characteristics, food matrix type, and detection methods determine the lower limit of detection. The use of chromatographic techniques for the analysis of mycotoxin in rice, wheat, oil-seed crops, peanuts, etc. has been described in various papers (Majeed et al., 2018). Aptamer and surface plasmon resonance are novel detection methods with high affinities and specificities and low detection limits, but only in a few food commodities like vegetable oils (Abdolmaleki et al., 2021). This shows that these methods have many potential applications for the future. In future research, their application to the detection of mycotoxins in other commodities will be important.

To eliminate or decrease levels of mycotoxin in food commodities below consumption levels, chemical, physical, and biological methods were used. During decontamination, food commodities' organoleptic properties and nutritional value should not be affected, and toxic degradation products should not be produced. Decontaminating mycotoxins efficiently poses a challenge in this regard. On the hand, controlling mycotoxigenic fungi with synthetic chemicals may cause a serious concern both at anthropogenic and ecological level. In this regard, eco-friendly mycotoxin management using plant's extract and EOs would be safer to the user and the environment. Use of such methodologies could be cost-effective and can be one of the aims of sustainable agriculture. Lastly, before application, safety issues of botanicals should be fully addressed in food commodities. Therefore, more research is required in order to standardize the quality of the natural extracts, evaluate their safety, and to conclude about the most effective moment of application as well as the most effective concentration for different food commodities.

Author contributions

AP: original draft preparation. MKS: wrote detection techniques from significant inputs from AP, AK, AS, and NKD: review and edit. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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