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Mycotoxins and Global Food Safety

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5.1 Introduction

Mycotoxins are toxic secondary metabolites produced by certain species of fungi, primarily *Aspergillus*, *Penicillium*, and *Fusarium*. These toxic compounds can contaminate a wide range of food products, including grains, nuts, fruits, and animal feeds, posing significant risks to human and animal health (Ibrahim & Menkovska, 2018; Kępińska-Pacelik & Biel, 2021; Awuchi et al., 2021, 2022; El-Sayed et al., 2022; Yu & Pedroso, 2023). Mycotoxins are chemically diverse, with over 400 identified varieties, each with distinct biological effects and toxicity levels (Janik et al., 2020; Awuchi et al., 2021, Leslie et al., 2021; El-Sayed et al., 2022). The issue of mycotoxin contamination has been recognized for centuries. Historical records suggest ancient incidents of food-borne illness likely caused by mycotoxins. One of the earliest documented instances is the outbreak of ergotism in the middle ages, caused by the consumption of rye contaminated with ergot alkaloids produced by *Claviceps purpurea* (Agriopoulou, 2021; Grzybowski et al., 2021; Ashfaq et al., 2024).

In today's globalized food system, the importance of addressing mycotoxins in food safety cannot be overstated. These contaminants are not only a threat to public health but also a significant economic burden due to crop losses, reduced livestock productivity, and trade restrictions (Eshetu et al., 2016; Imran et al., 2020; Mamo et al., 2020). The World Health Organization (WHO) and the Food and Agriculture Organization (FAO) have identified mycotoxins as critical food safety concerns, urging countries to implement stringent monitoring and control measures (Ayelign & De Saeger, 2020; Mamo et al., 2020; Meneely et al., 2023).

This chapter aims to provide a comprehensive overview of mycotoxins and their impact on global food safety. It explores the various types of mycotoxins, their sources and occurrence, and the health implications associated with exposure. In addition, the methods used for detecting and analyzing mycotoxins, the regulatory frameworks established to control their presence in food, and the strategies employed to prevent and mitigate contamination are examined. The chapter also discusses the economic and social implications

 DOI: 10.1201/9781003500605-6

of mycotoxin contamination and highlights global initiatives aimed at addressing this critical issue. Finally, future perspectives and research directions to improve the understanding and management of mycotoxins in the food supply are considered. By delving into these aspects, this chapter seeks to underscore the importance of mycotoxins in the broader context of global food safety and to highlight the need for continued vigilance and innovation in managing these insidious contaminants.

5.2 Types of Mycotoxins

Mycotoxins are a diverse group of toxic compounds produced by various fungi. Understanding the different types of mycotoxins, their sources, and their effects on the public health is crucial for developing effective food safety strategies. The diversity and complexity of mycotoxins necessitate the development of comprehensive monitoring and regulatory efforts to ensure food safety on a global scale (Marroquín-Cardona et al., 2014; Adeyeye et al., 2022; Chilaka et al., 2022; Zhang et al., 2024). The most significant mycotoxins in terms of their prevalence, toxicity, and impact on human and animal health are summarized in Table 5.1.

5.2.1 Aflatoxins

Aflatoxins are produced primarily by *Aspergillus flavus* and *Aspergillus parasiticus* (Ting et al., 2020; Nikolić et al., 2021; Lorán et al., 2022). They are highly toxic and carcinogenic, commonly found in crops such as corn, peanuts, cottonseed, and tree nuts (García & Heredia, 2014; Awuchi et al., 2020; Tumukunde et al., 2020; Smith, 2020). The various types of aflatoxins include aflatoxins B1, B2, G1, G2, and M1.

5.2.2 Ochratoxins

Ochratoxins are produced by *Aspergillus* and *Penicillium* species, with ochratoxin A being the most significant due to its prevalence and toxicity (Khoi et al., 2021; Więckowska et al., 2023). It is commonly found in cereals, coffee, dried fruits, wine, and grape juice.

5.2.3 Fusarium Toxins

Fusarium species produce several important mycotoxins that affect cereals such as wheat, maize, and barley (Gallo et al., 2022; Kościelecka et al., 2023). The various types of *Fusarium* toxins include deoxynivalenol (DON); zearalenone (ZEA); fumonisins; and fumonisin B1, T-2, and HT-2 toxins.

TABLE 5.1

Types of Mycotoxins and Their Effects on Human and Animal Health

Class of Mycotoxin	Sources	Crops Affected	Examples	Effects	References
Aflatoxin	*Aspergillus flavus* and *Aspergillus parasiticus*	Corn, peanuts, cottonseed, and tree nuts. It can also be found in dairy products.	Aflatoxin B1, B2, G1, G2, M1	It causes liver cancer. Chronic exposure can lead to liver cirrhosis and hepatocellular carcinoma.	Mungamuri & Benkerroum, 2020; Singh et al., 2021; Cao et al., 2022; Wang et al., 2023.
Ochratoxin	*Aspergillus* and *Penicillium* species	Cereals, coffee, dried fruits, wine, and grape juice.	Ochratoxin A (OTA)	It can cause kidney damage and has been linked to kidney and liver tumors. It can also impair immune function and has teratogenic effects.	Benkerroum, 2020; Khoi et al., 2021; Nour-bakhsh & Tajbakhsh, 2021; Longobardi et al., 2022; Stoev, 2022; Więckowska et al., 2023.
Fusarium Toxins	*Fusarium* species	Cereals such as wheat, maize, and barley.	Deoxynivalenol (DON); zearalenone (ZEA); fumonisins; and fumonisin B1, T-2, and HT-2 toxins	It causes nausea, vomiting, diarrhea, and immune suppression. It disrupts reproductive systems in animals, causing infertility, abortion, and other reproductive issues.	Pestka, 2007; Althouse et al., 2019; Rai et al., 2020; Zhou et al., 2020; Ekwomadu et al., 2021; Gallo et al., 2022; Kościelecka et al., 2023.
Patulin	*Penicillium*, *Aspergillus*, and *Byssochlamys* species	Rotting apples and apple products.	Patulin	Associated with gastrointestinal disturbances and immunotoxicity. It has shown potential carcinogenic properties in animal studies.	Ramalingam et al., 2019; Zhai et al., 2019; Wei et al., 2020; Zheng et al., 2021; Fan & Hu, 2024; Wang et al., 2024.
Ergot Alkaloids	*Claviceps* species	Rye and other cereals.	Ergotamine and ergometrine	It causes vasoconstriction, leading to severe health issues such as hallucinations, convulsions, and gangrene.	Al-Omari et al., 2018; Liu, 2018; Yonpiam, 2018; Ashfaq et al., 2024; Berraies et al., 2024.

TABLE 5.1 ***(Continued)***

Types of Mycotoxins and Their Effects on Human and Animal Health

Class of Mycotoxin	Sources	Crops Affected	Examples	Effects	References
Citrinin	*Penicillium* and *Aspergillus* species	Stored grains and cereals.	Citrinin	Known to cause kidney damage. It can also affect liver function and has been observed to cause cytotoxic effects in various cell lines.	Gupta et al., 2018, Silva et al., 2020; Gupta et al., 2022; de Menezes et al., 2023.
Alternaria Toxins	*Alternaria* species	Various fruits, vegetables, tomatoes, apples, and cereals.	Alternariol (AOH), alternariol monomethyl ether (AME)	It can disrupt endocrine function and has shown mutagenic properties in laboratory studies.	Crudo et al., 2019; Hohenbichler et al., 2020; Aichinger et al., 2021; Louro et al., 2024.
Sterigmatocystin	*Aspergillus* species	Grains, cheese, and other foods.	Sterigmatocystin	It is a potent carcinogen and has been linked to liver and kidney cancers.	Nieto et al., 2018; Viegas et al., 2020; Zingales et al., 2020; Zhou et al., 2023.

5.2.4 Patulin

Patulin is produced by *Penicillium*, *Aspergillus*, and *Byssochlamys* species and is commonly found in rotting apples and apple products (Wei et al., 2020; Zheng et al., 2021; Fan & Hu, 2024).

5.2.5 Ergot Alkaloids

Ergot alkaloids produced by *Claviceps* species contaminate rye and other cereals, causing ergotism (Liu, 2018; Ashfaq et al., 2024). Ergotamine and ergometrine are the most significant.

5.2.6 Citrinin

Citrinin is produced by *Penicillium* and *Aspergillus* species, commonly found in stored grains and cereals (Gupta et al., 2022; de Menezes et al., 2023). It often occurs alongside ochratoxin A in contaminated foods.

5.2.7 Alternaria Toxins

Produced by *Alternaria* species, these mycotoxins are found in various fruits, vegetables, and grains (Aichinger et al., 2021; Louro et al., 2024). The main *Alternaria* toxins are alternariol (AOH) and alternariol monomethyl ether (AME).

5.2.8 Other Mycotoxins

Other mycotoxins include sterigmatocystin, produced by *Aspergillus* species (Zhou et al., 2023), and various emerging mycotoxins whose impacts are still being studied. They include enniatins, beauvericin, and moniliformin, which are gaining attention for their potential health impacts. Enniatins and beauvericin are ionophoric mycotoxins with antimicrobial and cytotoxic activities (Hasuda & Bracarense, 2023), while moniliformin affects cardiovascular health (Singh & Kumari, 2022).

5.3 Sources and Occurrence of Mycotoxins

Mycotoxins are ubiquitous in nature and can contaminate a wide range of agricultural products (Tola & Kebede, 2016; El-Sayed et al., 2022). Their presence in food and feed is influenced by various environmental, biological, and agricultural factors (Pleadin et al., 2019; Kępińska-Pacelik & Biel, 2021). Knowing the sources, occurrences, and conditions that favor mycotoxin production and proliferation is crucial for developing effective prevention and control strategies to ensure food safety.

5.3.1 Natural Occurrence in Crops

Mycotoxins are primarily produced by fungi during the growth, harvest, and storage of crops. The most common mycotoxin-producing fungi include species from the genera *Aspergillus*, *Penicillium*, *Fusarium*, and *Alternaria* (Sainz et al., 2018; Kaur & Verma, 2023). These fungi can infect crops both pre-harvest (in the field) and post-harvest (during storage and processing). In pre-harvest contamination, crops can be infected with mycotoxin-producing fungi while still in the field. Factors such as temperature, humidity, rainfall, and insect damage can influence fungal growth and mycotoxin production (Awuchi et al., 2021; Kos et al., 2023). For example, aflatoxins are commonly produced in hot, humid climates, while *Fusarium* toxins are more prevalent in cooler, temperate regions (Kos et al., 2023; Casu et al., 2024; Rangel-Muñoz et al., 2024). On the other hand, in post-harvest contamination, improper drying and storage conditions can lead to fungal growth and mycotoxin production. High moisture levels and warm temperatures in storage facilities create an ideal environment for fungal proliferation (Brambilla & Sangiorgio, 2020; Meno et al., 2021; Amobonye et al., 2023).

5.3.2 Factors Influencing Mycotoxin Production

Several factors can influence the production of mycotoxins in crops. They include

- **Climatic Conditions**: Temperature, humidity, and rainfall are critical factors. For instance, aflatoxin production is favored by high temperatures and high humidity, common in tropical and subtropical regions (Shekhar et al., 2018; Dövényi-Nagy et al., 2020). In contrast, cooler temperatures and wet conditions favor the production of *Fusarium* toxins like deoxynivalenol and zearalenone (Milani, 2013; Huang et al., 2023).
- **Agricultural Practices**: Farming practices such as crop rotation, irrigation, use of fertilizers, and pest control can affect fungal growth (Shah et al., 2021; Richard et al., 2022). For example, monoculture cropping systems can increase the risk of fungal infections.
- **Genetic Susceptibility**: Some crop varieties are more resistant to fungal infections and mycotoxin production. Breeding for resistance is an important strategy in managing mycotoxin risk (Buerstmayr & Lemmens, 2015; Rose, 2018)
- **Insect Damage**: Insects can create entry points for fungal infections and contribute to the spread of mycotoxin-producing fungi within crops (Biemond et al., 2021; Leslie et al., 2021).

5.3.3 Commonly Affected Foods

Mycotoxins can contaminate a wide range of food and feed products. The most commonly affected commodities include cereals and grains (corn, wheat, barley, oats, and rice are particularly susceptible to contamination by aflatoxins, ochratoxins, and *Fusarium* toxins) (El-Sayedet al., 2022; Gurikar et al., 2023), nuts and oilseeds (peanuts, almonds, pistachios, and cottonseed are prone to aflatoxin contamination) (Bhat & Reddy, 2017; El-Sayed et al., 2022), fruits and vegetables (apples, grapes, and other fruits can be contaminated by patulin and *Alternaria* toxins) (Nan et al., 2022; Bacha et al., 2023). Other foods affected include dairy products (aflatoxin M1 can be found in milk and dairy products via the ingestion of contaminated feeds by animals) (Min et al., 2021; Turna & Wu, 2021), spices and herbs (spices such as paprika, chili, and black pepper can be contaminated with aflatoxins and ochratoxins) (Syamilah et al., 2022; Demirhan & Demirhan, 2023) and animal feed(contaminated feed can lead to mycotoxin accumulation in animal tissues, milk, and eggs, posing indirect risks to human health) (Haque et al., 2020; Awuchi et al., 2022).

5.3.4 Geographical Distribution

The geographical distribution of mycotoxins varies based on climate, agricultural practices, and crop types. Aflatoxins are predominantly found in tropical and subtropical regions, affecting crops such as corn, peanuts, and tree nuts in countries like India, China, and Nigeria (Awuchi et al., 2020; Kaale et al., 2021; Meneely et al., 2023). Ochratoxins are found in a variety of climates, but especially in temperate regions, affecting cereals, coffee, dried fruits, and wine in Europe, North America, and parts of Asia (Li et al., 2021; Ganesan et al., 2022; González-Curbelo et al., 2023). *Fusarium* toxins are common in temperate regions, affecting wheat, barley, and maize in North America, Europe, and parts of Asia (El-Sayed et al., 2022; Kos et al., 2023). Patulins are found worldwide, particularly in apples and apple products, with significant occurrences reported in North America and Europe (Zhong et al., 2018; Vidal et al., 2019; Gomes et al., 2021).

5.3.5 Examples of Mycotoxin Outbreaks

Several notable mycotoxin outbreaks highlight the widespread impact of these contaminants. An outbreak of aflatoxicosis (turkey X disease)(1960s, UK) that killed over 100,000 turkey poults was traced back to peanut meal contaminated with aflatoxins (Ditta et al., 2018; Balan et al., 2024; Abdelhameed & Khalifa, 2024). High levels of fumonisins (fumonisin outbreak) (1989, USA) in corn were linked to cases of equine leukoencephalomalacia and porcine pulmonary edema (Smith, 2018; Wangia-Dixon & Nishimwe, 2020; Riet-Correa et al., 2024). High levels of Ochratoxin A (ochratoxin contamination) (2004, Europe) were found in baby food products, leading to recalls and heightened regulatory scrutiny (Kabak, 2012; Ozden et al., 2012; Hampikyan et al., 2015).

5.4 Health Impacts of Mycotoxins

Mycotoxins pose significant health risks to both humans and animals. Their effects can range from acute toxicity to chronic health problems, including cancer, immune suppression, and reproductive disorders. Understanding these health impacts is crucial for assessing the risks associated with mycotoxin exposure and implementing effective food safety measures to protect public health. Table 5.2 gives a summary of the health impacts of mycotoxins.

5.5 Detection and Analysis of Mycotoxins

Effective detection and analysis of mycotoxins are critical components to ensuring food safety and protecting public health (Adeyeye et al., 2022). Various analytical methods have been developed to detect and quantify

TABLE 5.2

Health Impacts of Mycotoxins

Health Impacts	Types of Mycotoxins Involved	Effects	References
Acute toxicity; acute mycotoxin toxicity often results from high doses consumed in a short period.	Aflatoxins, deoxynivalenol (DON), T-2 toxin, patulin	It can cause liver damage, jaundice, nausea, vomiting, diarrhea, abdominal pain, gastrointestinal distress, and even death.	Barac, 2019; Awuchi et al., 2021, 2022.
Chronic toxicity; chronic exposure to mycotoxins, even at low levels, can lead to long-term health issues that may not be immediately apparent.	Aflatoxins, ochratoxin A (OTA), fumonisins, zearalenone (ZEA), citrinin	It can cause immune suppression, stunted growth in children, and malnutrition. Chronic exposure can cause chronic kidney disease and disrupt endocrine function.	Tesfamariam et al., 2020; Kadan & Aral, 2021; Ráduly et al., 2021; Awuchi et al., 2022; Kościelecka et al., 2023.
Carcinogenicity; several mycotoxins are classified as carcinogens due to their ability to cause cancer in humans and animals.	Aflatoxin B1, ochratoxin A, fumonisin B1, sterigmatocystin	It is linked to liver and kidney cancers.	Ahmed-Adam et al., 2017; Chhonker et al., 2018; Omotayo et al., 2019; Awuchi et al., 2021, 2022; Yu & Pedroso, 2023; Gurikar et al., 2023.
Immunotoxicity; mycotoxins can impair the immune system, making individuals more susceptible to infections and diseases.	Aflatoxins, ochratoxin A, deoxynivalenol	Known to suppress the immune system, leading to increased susceptibility to infectious diseases and reduced vaccine efficacy. It can also cause chronic inflammatory diseases.	Pierron et al., 2016; Brown et al., 2021; Kraft et al., 2021; Awuchi et al., 2022; Saha Turna et al., 2023.
Reproductive and developmental toxicity; some mycotoxins can affect reproductive health and development, leading to birth defects and reproductive disorders.	Ochratoxin A, fumonisins, zearalenone	Mimics estrogen and can disrupt the reproductive system, leading to infertility, miscarriages, and developmental issues in offspring.	Malir et al., 2013; Eze et al., 2018; El. Khoury et al., 2019; Gönenç et al., 2020; Awuchi et al., 2022; Kościelecka et al., 2023.
Neurotoxicity; certain mycotoxins can affect the nervous system, leading to neurological disorders.	Fumonisins, T-2 toxin	Can cause severe neurological symptoms such as tremors, seizures, and brain damage in cases of high exposure.	Evans & Gupta, 2018; Barac, 2019; Janik et al., 2020; Richard et al., 2020; Nguyen et al., 2022.

mycotoxins in food and feed products. These methods range from traditional chromatographic techniques to modern biosensors.

5.5.1 Sampling and Preparation

The accuracy of mycotoxin analysis depends on proper sampling and sample preparation. Representative sampling is crucial due to the heterogeneous distribution of mycotoxins in bulk commodities (Rivas Casado et al., 2009; Wagner, 2015). Methods such as composite sampling (combining multiple samples) are used to ensure a more accurate representation of the contamination level (Ghosh et al., 2014). Samples must be prepared to isolate mycotoxins from the food matrix. This often involves grinding, homogenization, and extraction using solvents like methanol, acetonitrile, or water (Cigić & Prosen, 2009; Nakhjavan et al., 2020). Clean-up steps, such as solid-phase extraction (SPE), are used to remove interfering substances (Ötles & Kartal, 2016).

5.5.2 Chromatographic Techniques

Chromatographic methods are widely used for the detection and quantification of mycotoxins due to their accuracy and sensitivity. These include:

5.5.2.1 High-Performance Liquid Chromatography

High-performance liquid chromatography (HPLC) is a robust and widely used method for mycotoxin analysis. It often incorporates UV or fluorescence detection to identify and quantify mycotoxins (Turner et al., 2009; Singh & Mehta, 2020). For example, aflatoxins can be detected using HPLC with fluorescence detection after post-column derivatization (Shuib et al., 2017).

5.5.2.2 Liquid Chromatography-Mass Spectrometry

Liquid chromatography-mass spectrometry (LC-MS) combines the separation capabilities of liquid chromatography with the sensitivity and specificity of mass spectrometry. It is particularly useful for detecting multiple mycotoxins in a single run, making it a powerful tool for comprehensive mycotoxin screening (Malachová et al., 2018; Kunzet al., 2020).

5.5.2.3 Gas Chromatography-Mass Spectrometry

Gas chromatography-mass spectrometry (GC-MS) is used for volatile and semi-volatile mycotoxins, such as trichothecenes. Derivatization is often required to make the mycotoxins volatile for analysis (Köppen et al., 2010; Alsharif et al., 2015; Xu et al., 2021).

5.5.3 Immunochemical Methods

Immunochemical methods use antibodies to detect mycotoxins. These methods are often faster and more cost-effective than chromatographic techniques (Alsharif et al., 2015; Singh & Mehta, 2020; Raysyan et al., 2020; Alhazmi & Albratty, 2023).

5.5.3.1 Enzyme-Linked Immunosorbent Assay

Enzyme-linked immunosorbent assay (ELISA) is a widely used method for mycotoxin detection due to its simplicity, speed, and cost-effectiveness. It uses antibodies specific to the mycotoxin to capture and quantify the toxin based on colorimetric changes (Rahman et al., 2019; Majdinasab et al., 2020). ELISA kits are available for various mycotoxins, including aflatoxins, ochratoxins, and fumonisins.

5.5.3.2 Lateral Flow Devices

Lateral flow devices (LFDs), or rapid test strips, are userfriendly and provide quick results. They are commonly used for on-site testing of mycotoxins (Cvak et al., 2021; Wang et al., 2022). These devices work similarly to pregnancy tests, where a visible line indicates the presence of the mycotoxin.

5.5.4 Emerging Technologies

Advances in technology have led to the development of novel methods for mycotoxin detection.

5.5.4.1 Biosensors

Biosensors use biological molecules, such as enzymes or antibodies, to detect mycotoxins (Shrivastava & Sharma, 2022; Wang et al., 2022; Jubeen et al., 2024; Szelenberger et al., 2024). They offer high sensitivity and rapid detection. Examples include electrochemical biosensors, optical biosensors, and nanoparticle-based biosensors.

5.5.4.2 Molecular Techniques

Polymerase chain reaction (PCR) and quantitative PCR (qPCR) can detect the presence of mycotoxin-producing fungi by identifying specific DNA sequences (Rahman et al., 2019; Buslyk et al., 2022). These techniques are useful for predicting potential mycotoxin contamination.

5.5.4.3 Portable Devices

Portable devices, such as handheld spectrometers, are being developed for field testing of mycotoxins. These devices provide rapid and on-site analysis, which is particularly useful for farmers and food inspectors (Kademi et al., 2019; Jafari et al., 2021).

5.5.5 Challenges and Future Directions

Detecting and analyzing mycotoxins present several challenges, including the need for high sensitivity, specificity, and the ability to handle complex food matrices. Challenges such as matrix effects, the need for multi-mycotoxin detection, and the cost of analysis still exist (Agriopoulou et al., 2020; Iqbal, 2021). Complex food matrices can interfere with the detection of mycotoxins (Agriopoulou et al., 2020; Notardonato et al., 2021); hence, there is a need to develop effective sample clean-up and validation procedures. Standardization and rigorous validation of analytical techniques is required to ensuring consistent and reliable results across different laboratories (Peris-Vicente et al., 2015). In addition, developing methods capable of simultaneously detecting multiple mycotoxins is crucial due to the frequent co-occurrence of mycotoxins in food and feed. Reducing the cost and increasing the accessibility of mycotoxin detection methods, especially in developing countries, is essential for global food safety (Agriopoulou et al., 2020; Ndemera et al., 2020; Adeyeye et al., 2022).

5.6 Regulatory Standards and Guidelines of Mycotoxins

Regulatory standards and guidelines for mycotoxins are essential for ensuring food safety and protecting public health. International organizations, such as the Codex Alimentarius, together with national regulatory bodies, have established limits for mycotoxin levels in food and feed (Ibrahim & Menkovska, 2018; López-García, 2022). Effective monitoring, enforcement, and ongoing adaptation to emerging challenges are critical for managing mycotoxin risks and ensuring compliance with regulatory standards (López-García, 2022; Chilaka et al., 2022; Zhang et al., 2024). These regulations aim to minimize the risk of mycotoxin exposure and its associated health impacts.

5.6.1 International Standards

Several international organizations provide guidelines and standards for mycotoxin levels in food and feed (Duarte et al., 2010; Eskola et al., 2020; López-García, 2022). These standards help harmonize regulations across different countries and ensure global food safety.

5.6.1.1 Codex Alimentarius Commission

Codex Alimentarius Commission is jointly established by the Food and Agriculture Organization and the World Health Organization, the Codex

Alimentarius Commission develops international food standards, guidelines, and codes of practice (Halabi, 2015; Lee et al., 2021; Fink, 2023; Fortin, 2023). The Codex sets maximum levels for aflatoxins in various foods, such as 10 μg/kg for ready-to-eat peanuts and 0.5 μg/kg for aflatoxin M1 in milk (EFSA, 2018, 2020; Musawa, 2022; Schincaglia et al., 2023). The maximum level for ochratoxin A in cereals and cereal products is 5 μg/kg (Majeed et al., 2018; Celik & Kabak, 2022; Ben Miri et al., 2024). The Codex recommends a maximum level of 2 mg/kg for deoxynivalenol in cereal grains and 4 mg/kg for fumonisins (B1 + B2) in maize and maize products (Hanvi et al., 2019; Iqbal et al., 2020; Mahdjoubi et al., 2020).

5.6.2 European Union Regulations

The European Union (EU) has stringent regulations for mycotoxins in food and feed, enforced by the European Food Safety Authority (EFSA) and the European Commission (Cheli et al., 2014; Chilaka et al., 2022; Sorbo et al., 2022; Poroșnicu et al., 2023). Maximum levels are set for various foods, including 2 μg/kg for aflatoxin B1 in cereals and 4 μg/kg for total aflatoxins in groundnuts (EFSA, 2018, 2020). The maximum level for OTA is 3 μg/kg in cereals and 10 μg/kg in dried vine fruit and 1.75 mg/kg for DON in unprocessed wheat and 0.75 mg/kg in wheat-based products (Tantaoui-Elaraki et al., 2018; Agriopoulou et al., 2020). The maximum level is 4 mg/kg for fumonisins (B1 + B2) in maize intended for human consumption and 100 μg/kg for zearalenone (ZEA) in cereals and 50 μg/kg in cereal-based products (EFSA, 2014; Leite et al., 2021; Janić Hajnal et al., 2023).

5.6.3 National Regulations

Various countries have their own regulations and guidelines for the acceptable level of mycotoxins in food and feed that often align with international standards (Table 5.3). These limits align with international standards set by organizations such as Codex Alimentarius to ensure that food products meet global safety requirements

5.6.4 Monitoring and Enforcement

Effective monitoring and enforcement are critical for ensuring compliance with mycotoxin regulations. Regulatory agencies employ various strategies to monitor mycotoxin levels in food and feed, including regular sampling and analysis of food and feed products to detect mycotoxin contamination, evaluating the risk of mycotoxin exposure based on consumption patterns and contamination levels. They also conduct inspections of food production, storage, and distribution facilities to ensure adherence to regulations and also educate producers, processors, and consumers about mycotoxin risks and prevention measures (Omojokun, 2013; Fumagalli et al., 2021; Chatterjee et al., 2023).

TABLE 5.3
National Regulations for Mycotoxins in Food and Feed

Country	Regulatory Organization	Type of Mycotoxins/ Food or Feed	Maximum Allowable Limit	References
United States	Food and Drug Administration (FDA) and the Department of Agriculture (USDA)	Aflatoxin M1 in milk	0.5 μg/kg	Kos et al., 2014; Sangvikar, 2021.
		DON for finished wheat products	1 mg/kg	Chen et al., 2021; Mishra et al., 2022.
		DON for animal feed	5 mg/kg	Pack et al., 2021; Mishra et al., 2022.
		Fumonisins for maize products (human consumption)	2 mg/kg	Wu, 2004, 2006; Sabillón et al., 2023.
		Fumonisins for maize products (animal feed)	5 mg/kg	Wu, 2004, 2006; Sabillón et al., 2023
		ZEA in grains and animal feed	None, but the USDA monitors	Abdallah et al., 2015; Weaver et al., 2021.
Canada	Health Canada and the Canadian Food Inspection Agency (CFIA)	Aflatoxins in human food	15 μg/kg	Bhardwaj et al., 2023; Meneely et al., 2023.
		OTA in cereal grains and grains products	15 μg/kg	Shi et al., 2019; Yu & Pedroso, 2023
		DON for unprocessed wheat	2000 μg/kg	Chen et al., 2021; Gedion, 2022.
		DON in wheat (human consumption)	1000 μg/kg	Bosompem, 2020; Chen et al., 2021.
		Fumonisins for maize and maize products (human consumption)	2000 μg/kg	Donnelly et al., 2022; Gedion, 2022.
		ZEA in maize and maize products	100 μg/kg	Donnelly et al., 2022; Gedion, 2022; Stoev, 2024.
Japan	The Ministry of Health, Labour, and Welfare	Aflatoxin B1 in all foods	10 μg/kg	Benkerroum, 2020; Yoshinari et al., 2024.
		OTA in dried vine fruits	2 μg/kg	Özer, 2022; Fakhri et al., 2024.
		DON in wheat and wheat products	1100 μg/kg	Yoshinari et al., 2014; Nakamura et al., 2021.
		Fumonisins in corn and corn products	2000 μg/kg	Yoshinari et al., 2014; Kai et al., 2016.

TABLE 5.3 ***(Continued)***

National Regulations for Mycotoxins in Food and Feed

Country	Regulatory Organization	Type of Mycotoxins/ Food or Feed	Maximum Allowable Limit	References
Australia and New Zealand	Food Standards Australia New Zealand (FSANZ)	Aflatoxins in peanuts	15 µg/kg	Bhardwaj et al., 2023; Meneely et al., 2023.
		DON in wheat and wheat products	2000 µg/kg	Baines & Borradale, 2020; Eskola et al., 2020.
		OTA in cereal grains and grains products	5 µg/kg	Carballo et al., 2019; Eskola et al., 2020.
		Fumonisins in maize and maize products	2000 µg/kg	Carballo et al., 2019; Eskola et al., 2020; Meneely et al., 2023.
Nigeria	National Agency for Food and Drug Administration and Control (NAFDAC) and Standards Organization of Nigeria (SON)	Aflatoxin B1	2 µg/kg	Onyeke, 2020; Nahunnaro et al., 2021.
		Total Aflatoxins (B1, B2, G1, and G2) in foods	4 µg/kg	Ubwa et al., 2014; Tor et al., 2020;
		OTA in cereal grains and grains products	5 µg/kg	Olotu, 2018; Onyeke, 2020; Awuchi et al., 2021.
		DON in wheat and wheat products	2000 µg/kg	Atanda et al., 2013; Onyeke, 2020; Awuchi et al., 2021.
		Fumonisins for maize and maize products	2000 µg/kg	Onyeke, 2020; Badmos, 2021.

5.6.5 Challenges and Future Directions

Despite the established regulations, there exist some challenges on how to effectively manage imycotoxin risks. The disparities in regulatory limits and guidelines among various countries can significantly hinder international trade. Efforts are ongoing to harmonize mycotoxin standards globally. New mycotoxins and masked mycotoxins (mycotoxins modified by plant metabolism) pose challenges for detection and regulation (Kovač et al., 2018; Ekwomadu et al., 2021; Iqbal, 2021). Also, changing climatic conditions can alter the prevalence and distribution of mycotoxin-producing fungi, requiring adaptive regulatory measures (Van der Fels-Klerx et al., 2016; Kos et al., 2023; Casu et al., 2024). Therefore, continued development and validation of advanced detection methods are necessary to improve monitoring and enforcement capabilities.

5.7 Prevention and Control Strategies for Mycotoxins

Prevention and control of mycotoxin contamination require a multi-faceted approach, crucial for ensuring food safety and protecting public health. Strategies to mitigate mycotoxin risks involve a combination of agricultural practices, effective post-harvest handling, biological and chemical control methods, regulatory measures, and technological innovations (Table 5.4). By integrating these strategies, it is possible to reduce the risk of mycotoxin contamination and ensure the safety of food and feed products. These strategies aim to reduce the occurrence of mycotoxins at all stages of the food production and supply chain.

5.8 Economic and Social Implications of Mycotoxins

The economic and social implications of mycotoxin contamination are profound and multifaceted, affecting not only public health but also agricultural economies, trade, and livelihoods. Economic losses due to reduced crop yields, trade restrictions, and healthcare costs are significant. Mycotoxin contamination also exacerbates food insecurity and public health issues, particularly in developing countries, where agriculture is a significant part of the economy and food security is a major concern (Gbashi et al., 2018; Kebede et al., 2020; Ajmal et al., 2022; Nji et al., 2022). Addressing these implications requires comprehensive strategies that integrate prevention, control, education, and support for affected populations to mitigate the adverse effects and promote sustainable development (Logrieco et al., 2018; Ndemara et al., 2020; Ortega-Beltran & Bandyopadhyay, 2021).

5.8.1 Economic Implications

5.8.1.1 Losses in Agriculture and Food Industry

Mycotoxin contamination can lead to significant economic losses at various stages of the food supply chain. Mycotoxin-producing fungi can infect crops in the field, leading to yield losses and reduced quality. Contaminated crops may be unsuitable for sale or consumption, resulting in direct financial losses for farmers. Improper storage and handling can exacerbate mycotoxin contamination, causing further losses during transportation, storage, and processing. Post-harvest losses due to mycotoxins can be substantial, especially in regions lacking proper storage facilities and technologies (Chilaka et al., 2017; Neme & Mohammed, 2017; Olorunfemi & Kayode, 2021). In addition, food manufacturers may face significant financial burdens due to the

TABLE 5.4

Prevention and Control Strategies for Mycotoxi Contamination

Control Strategies	Practices	Effects
	Crop rotation and diversity	Rotating crops and planting diverse species can reduce the build-up of mycotoxin-producing fungi in the soil.
Agricultural practices	Resistant varieties	Developing and planting crop varieties using genetic engineering and traditional breeding techniques that are resistant to fungal infections can significantly reduce mycotoxin contamination.
	Optimal planting and harvesting times	Planting and harvesting crops at optimal times can minimize exposure to conditions favorable for fungal growth, such as high humidity and warm temperatures.
	Proper irrigation and drainage	Ensuring adequate irrigation and drainage prevents water stress, which can make crops more susceptible to fungal infections.
	Integrated pest management (IPM)	Using biological control agents, chemical pesticides, and cultural practices to manage pests and diseases reduces the risk of fungal infections that can lead to mycotoxin production.
Post-harvest handling and storage	Clean and sanitary storage	Keeping storage facilities clean and free from previous crop residues minimizes fungal contamination.
	Controlled atmosphere storage	Low oxygen and high carbon dioxide levels can inhibit fungal growth and mycotoxin production.
	Temperature and humidity control	Maintaining low temperatures and humidity levels in storage facilities is crucial for preventing fungal growth.
	Drying	Rapid and thorough drying of crops to safe moisture levels (typically below 13–14%) immediately after harvest prevents fungal growth.
Biological control	Biocontrol agents	Beneficial microbes such as non-toxigenic strains of *Aspergillus flavus* can be applied to crops to reduce aflatoxin contamination.
	Plant extracts and natural compounds	Plant extracts and natural compounds such as neem oil, garlic extract, and thyme oil with antifungal properties can be used to control fungal growth and mycotoxin production.
Chemical control	Fungicides	Applying fungicides during crop growth can help control fungal infections.
	Detoxification agents	Chemical agents such as ozone treatment, ammoniation, and the use of binding agents can help detoxify or degrade mycotoxins.

(*Continued*)

TABLE 5.4 ***(Continued)***

Prevention and Control Strategies for Mycotoxi Contamination

Control Strategies	Practices	Effects
Regulatory and policy measures	Regulatory standards Surveillance and monitoring Education and training	Establishing and enforcing maximum allowable levels of mycotoxins in food and feed ensures that contaminated products do not enter the market. Regular monitoring and surveillance programs help detect mycotoxin contamination early and prevent the distribution of contaminated products. Providing education and training to farmers, food processors, and consumers on mycotoxin risks and prevention methods is crucial for effective control.
	Support for research and development	Governments and organizations should support research and development of new technologies and methods for mycotoxin prevention and control.
Technological innovations	Biosensors and rapid detection kits	Developing rapid and cost-effective detection methods, such as biosensors and lateral flow devices, enables timely identification and management of mycotoxin contamination.
	Genetic engineering	Using genetic engineering to develop crops with enhanced resistance to mycotoxin-producing fungi can significantly reduce contamination levels.
	Blockchain and traceability systems	Implementing blockchain technology and traceability systems in the food supply chain help to ensure that mycotoxin levels are monitored and controlled at each stage.

need for mycotoxin testing, quality control measures, and potential recalls of contaminated products (Mitchell et al., 2016; Focker & van der Fels-Klerx, 2020; Chatterjee et al., 2023). These measures increase production costs and can impact profitability.

5.8.1.2 Trade Implications

Mycotoxin contamination can have severe implications for international trade, particularly for countries that rely on agricultural exports (Gbashi et al., 2018; Luo et al., 2021; López-García, 2022). Countries with strict mycotoxin regulations may reject contaminated imports, leading to trade restrictions and loss of export markets for affected countries. For example, the European Union has stringent limits on mycotoxins in imported food products, impacting exporters from regions with high contamination levels (Eskola et al., 2020; Luo et al., 2021; Chilaka et al., 2022; López-García, 2022). Mycotoxin contamination can also reduce the market value of agricultural commodities (Kebede et al., 2020; Luo et al., 2021). Contaminated products may be sold at lower prices or used for lower-value purposes, such as animal feed, resulting in reduced income for producers.

5.8.1.3 Healthcare Costs

The health impacts of mycotoxin exposure can lead to increased healthcare costs. Treating illnesses caused by mycotoxins, such as liver cancer, immune suppression, and acute poisoning, incurs significant healthcare costs (Mamo et al., 2020; Adeyeye et al., 2022). These costs can burden public health systems, especially in developing countries with limited healthcare infrastructure. Health issues related to mycotoxin exposure can reduce workforce productivity due to illness, absenteeism, and decreased capacity to work (Liew & Mohd-Redzwan, 2018; Sabino et al., 2019; Schlosser et al., 2020). This loss of productivity can have broader economic implications, affecting overall economic growth and development.

5.8.2 Social Implications

5.8.2.1 Food Security

Mycotoxin contamination directly impacts food security, particularly in regions where food availability and access are already limited (Moretti et al., 2017; Kebede et al., 2020; Nji et al., 2022). Contaminated crops and food products may be unsuitable for consumption, reducing the overall food supply. This can exacerbate food shortages and increase hunger and malnutrition, particularly among vulnerable populations. Economic losses due to mycotoxin contamination can reduce household income, limiting access to safe and nutritious food (Udomkun et al., 2017; Mamo et al., 2020; Adeyeye et al., 2022). This can have severe implications for food security and nutritional status, especially for low-income families.

5.8.2.2 Public Health

The public health implications of mycotoxin exposure are significant and multifaceted. Long-term exposure to mycotoxins, even at low levels, can lead to chronic health problems such as liver damage, cancer, immune suppression, and developmental issues in children (Kadan & Aral, 2021; Awuchi et al., 2022). These health impacts can reduce quality of life and increase morbidity and mortality rates. Acute mycotoxin poisoning, although less common, can cause severe and life-threatening symptoms (Awuchi et al., 2021, Navale et al., 2021). Outbreaks of acute aflatoxicosis, for example, have been reported in several countries, causing multiple fatalities (Kamala et al., 2018; Meijer et al., 2021).

5.8.2.3 Social Inequality

Mycotoxin contamination can exacerbate social inequalities, disproportionately affecting marginalized and vulnerable populations. Smallholder farmers, who often lack access to resources, technology, and education, are particularly vulnerable to mycotoxin contamination (Alberts et al., 2017; Chilaka et al., 2022; Nji et al., 2022). The economic losses they face can perpetuate poverty and limit opportunities for economic advancement. Women and children are often more affected by food insecurity and health issues related to mycotoxins. Women, as primary caregivers, bear the burden of caring for sick family members, while children are more susceptible to the health impacts of mycotoxins due to their developing bodies and higher consumption of staple foods (Tshalibe, 2019; Visser et al., 2020; Fredrick, 2021).

5.9 Global Initiatives and Collaboration

Global initiatives and collaboration are vital for effectively managing mycotoxin contamination and ensuring food safety. Various international organizations, regional bodies, research institutions, and governments work together to develop standards, conduct research, build capacity, and raise awareness to manage mycotoxin risks effectively (Logrieco et al., 2018; López-García, 2022; Zhang et al., 2024). Continued efforts in policy harmonization, technological innovation, and adaptation to emerging challenges are essential for mitigating the risks of mycotoxins and promoting sustainable agricultural practices worldwide (Logrieco et al., 2018; López-García, 2022; Chilaka et al., 2022). These initiatives aim to enhance food safety, improve public health, and support sustainable agricultural practices worldwide.

5.9.1 International Organizations

Several international organizations play pivotal roles in addressing mycotoxin contamination through research, policy development, and capacity-building initiatives. The Food and Agriculture Organizationworks to improve food security and safety by promoting good agricultural practices, providing technical assistance, and supporting research on mycotoxin management (Wagacha & Muthomi, 2008; Unnevehr & Grace, 2013; Grace et al., 2015; Xu et al., 2022). The FAO also collaborates with other organizations to develop guidelines and standards for mycotoxin levels in food and feed. The World Health Organization focuses on the public health aspects of mycotoxin contamination. It conducts risk assessments, provides health guidelines, and supports member countries in developing and implementing mycotoxin control measures (Dohlman, 2003; Wu, 2004; Sherif et al., 2009; López-García, 2022). Jointly established by the FAO and WHO, the Codex Alimentarius Commission develops international food standards, guidelines, and codes of practice to ensure food safety and facilitate international trade (Joint FAO/WHO, 2007; WHO, 2018; Godefroy, 2014; Fortin, 2023). The Codex sets maximum permissible levels for various mycotoxins in food and feed, providing a reference for national regulations.

5.9.2 Research and Development Collaborations

Research collaborations are crucial for advancing knowledge and developing innovative solutions for mycotoxin prevention and control. The International Maize and Wheat Improvement Center (CIMMYT) conducts research on improving maize and wheat production, including developing mycotoxin-resistant crop varieties (Ortiz et al., 2008; Mouton, 2014; Warburton & Williams, 2017). It collaborates with national and international partners to disseminate improved seeds and farming practices. The International Institute of Tropical Agriculture (IITA) works with local and international partners to develop and promote effective mycotoxin control strategies. Itfocuses on agricultural research in the tropics, including mycotoxin management in staple crops like maize and groundnuts (Ortiz et al., 2008; Bandyopadhyay et al., 2009; Grace et al., 2015; Xu et al., 2022).

5.9.3 Capacity Building and Education

Capacity building and education are essential for empowering stakeholders to implement effective mycotoxin control measures. International organizations and research institutions offer training programs for farmers, food processors, regulators, and health professionals on mycotoxin management (Alberts et al., 2017; Ndemara et al., 2020; Chilaka et al., 2022). These programs cover topics such as good agricultural practices, post-harvest handling, mycotoxin detection, and risk assessment. Organizations like the FAO and WHO provide technical assistance to countries in developing and implementing mycotoxin control strategies (Wagacha & Muthomi, 2008; Ndemara et al., 2020; Chilaka et al., 2022; López-García, 2022). This assistance includes support for laboratory infrastructure, regulatory frameworks, and surveillance programs. Raising awareness about the risks of mycotoxins and the importance of prevention measures is crucial for achieving widespread adoption of control strategies. Public awareness campaigns target various stakeholders, including farmers, consumers, and policymakers.

5.9.4 Policy and Regulatory Harmonization

Harmonizing mycotoxin regulations at the international level is vital for ensuring food safety and facilitating trade. The Codex Alimentarius Commission plays a key role in developing international standards for mycotoxin levels in food and feed (Duarte et al., 2010; Logrieco et al., 2018; López-García, 2022). These standards serve as benchmarks for national regulations and help ensure consistency and safety in the global food supply. International trade agreements often include provisions for food safety, including mycotoxin regulations. Harmonizing these regulations helps prevent trade barriers and ensures that food products meet safety standards across different countries (Hammoudi et al., 2009; Handford et al., 2015).

5.10 Future Perspectives and Research Directions on Mycotoxins

As the global food system faces increasing challenges from climate change, population growth, and evolving agricultural practices, addressing mycotoxin contamination remains a critical priority. Future perspectives and research directions must focus on innovative approaches, interdisciplinary collaborations, and proactive strategies to mitigate mycotoxin risks and enhance food safety. The development of rapid, accurate, and cost-effective detection methods for mycotoxins is essential for timely intervention and control. Advancements in biosensor technology, including nano-biosensors and lab-on-a-chip devices, offer promising solutions for real-time, on-site detection of mycotoxins in food and feed (Arora, 2018; Bhattacharya et al., 2022; Jafari, 2022). High-resolution mass spectrometry (HRMS) and tandem mass spectrometry (MS/MS) are becoming increasingly important for the precise quantification and identification of mycotoxins and their metabolites (Senyuva et al., 2015; Jensen et al., 2019; Arroyo-Manzanares et al., 2021). Developing portable and user-friendly diagnostic kits that can be used in the field by farmers and food processors can significantly improve early detection and reduce contamination levels.

Future perspectives and research directions in mycotoxin management should focus on advancing detection technologies, biological control methods, and genetic engineering to reduce contamination at the source. Climate change adaptation, innovations in storage and processing, and strengthened policy frameworks are essential for mitigating mycotoxin risks (Loi et al., 2023; Eruaga, 2024). Education and awareness initiatives, coupled with targeted research on health impacts and sustainable practices, will play a critical role in ensuring food safety and protecting public health in the face of evolving challenges. Through interdisciplinary collaborations and proactive strategies, the global community can effectively address mycotoxin contamination and promote a safer and more resilient food system (Fan et al., 2021; WHO, 2022; Eruaga, 2024).

Investigating the occurrence, toxicity, and health impacts of masked and emerging mycotoxins is crucial for comprehensive risk assessment. Also, conducting epidemiological studies to better understand the long-term health effects of mycotoxin exposure and identifying vulnerable populations can inform public health interventions (Wu et al., 2014; Alberts et al., 2017;

Phillips et al., 2022). Assessing the economic impacts of mycotoxin contamination on different sectors of the economy can help in prioritizing resources and policy measures. In addition, exploring sustainable agricultural practices, such as agroecology and organic farming, can provide holistic solutions for reducing mycotoxin risks while promoting environmental health (Bertola et al., 2021; Gomiero, 2018, 2021; Ratnadass et al., 2023).

5.11 Conclusion

Mycotoxins present a significant threat to global food safety, impacting public health, agriculture, and economies worldwide. Understanding the complexities of mycotoxin contamination and its wide-reaching effects is essential for developing effective prevention and control strategies. This chapter has explored the various facets of mycotoxin contamination, from types and sources to health impacts and economic implications, providing a comprehensive overview of the current state of knowledge and ongoing efforts to address this critical issue. Key strategies for mitigating mycotoxin risks include implementing good agricultural practices, improving post-harvest handling and storage, advancing detection and analysis technologies, and enforcing stringent regulatory standards. Looking ahead, future perspectives and research directions emphasize the need for innovative solutions, interdisciplinary approaches, and adaptive strategies to tackle the evolving challenges posed by mycotoxins. In conclusion, addressing mycotoxin contamination requires a coordinated global effort that integrates scientific research, policy development, and practical interventions. By leveraging the collective expertise of international organizations, researchers, policymakers, and industry stakeholders, we can mitigate the risks of mycotoxins, safeguard public health, and promote a more secure and resilient food system. Continued commitment to innovation, collaboration, and education will be essential in overcoming the challenges posed by mycotoxins and achieving sustainable food safety for future generations.

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