Chapter 12
Mycotoxins in Environment and Its Health Implications

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Abstract Mycotoxins are secondary metabolites produced by toxigenic molds under suitable conditions such as high temperature, moisture, etc. Stored foods are more susceptible to fungal growth and subsequent mycotoxins contamination. Mycotoxins are mutagenic, carcinogenic, immune-suppressive, and make the host susceptible to infectious diseases. Several methods can be used for mycotoxin detection, but enzyme-linked immunosorbent assay (ELISA) is proved to be the cost-effective method. Management strategies are very important in reducing the mycotoxicosis risk. This threat can be reduced by mitigation measures such as chemical methods, antagonistic activities, biodegradation, irradiation, heat, etc. Aflatoxin is one of the most hazardous and widespread mycotoxins contaminating foodstuffs. It is produced by different strains of *Aspergillus* species in a variety of products, such as cereals, pulses, coffee, wine, grape juice, and dried fruits. Mycotoxins monitoring in food and feed stuff fruits has become an important issue worldwide because of both the impact on human health and the high economic losses that is associated with crop production. Mold growth of *A. flavus* and *A. parasiticus* is stimulated to produce aflatoxins in conditions of high temperature, high humidity level, pest invasion, drought, high water activity, and adverse weather conditions in field as well as in storage godowns. Food commodities susceptible to mycotoxins contamination include wheat, rice, barley, maize, milk, peanuts, almonds, figs, pistachios, dried apricots, mulberries, dates, walnuts, spices, meat, etc. These toxins may persist in cereals even after mold destruction. However, the amount of toxin is reduced by several processes up to 20% including thermal food processing. Exposure to these chemicals causes wide variety of human disorders such as birth defects, reproductive disorders, mental problems, kidney and liver

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dysfunction, and immune system suppression. Diet is one of the main routes of exposure to these toxic chemicals. Mycotoxin contaminates the food commodities which is the major public health threat. These toxins are usually transferred during the processing of contaminated ingredients or seeds. So they bind to the plasma proteins of human body and persist there.

12.1 Introduction

12.1.1 Turkey X Disease and Discovery of Mycotoxins

The term mycotoxicology refers to the toxic effects caused by fungal mycotoxins. Modern mycotoxicology started with the discovery of aflatoxins in the early 1960s when the peanut-based feed caused the Turkey X disease and more than 10,000 turkeys and chickens were found dead in England (Blount 1961). It was then named as Turkey X disease and is considered as a turning point for the use of the term mycotoxins. Early investigations on Turkey X disease revealed neurological symptoms followed by coma and finally death in chickens intoxicated by eating mycotoxin-contaminated meals (Wannop 1961). The original description of Turkey "X" disease by Blount (1961) was that the turkeys in England dying of intoxication exhibited both clinical and gross pathologic signs. Catarrhal and hemorrhagic enteritis was a major sign along with the characteristic position assumed by poults dying, as described by Blount (1961), that the neck of poult would be tilted and the head flown back (opisthotonus) and legs would be sprawled completely toward the back (Richards 2008).

As studies were carried out to identify the etiology of Turkey "X" disease in England, no significant organisms were isolated from Brazilian groundnut meal; instead, microscopic examination revealed the presence of some fungal elements. However, a similar outbreak like Turkey "X" disease was reported from Kenya shortly thereafter by eating Ugandan groundnut meal. Investigations on Ugandan groundnut resulted in isolation of *Aspergillus* species that later on identified as *Aspergillus flavus*. The causative agent of Turkey X disease was then determined as aflatoxin. There is an array of highly cogent carcinogens being produced by the most abundant fungi like *A. flavus* and *Aspergillus parasiticus*. Further studies revealed isolation and identification of major aflatoxins, B1, B2, G1, and G2, using thin-layer chromatography (Armbrecht et al. 1963).

Afterward, many new fungal contagions were identified and characterized. Mycotoxins are secondary metabolites of fungi. Many genera of fungi have the potential to produce mycotoxins like *Aspergillus*, *Penicillium*, and *Fusarium* spp. Mycotoxins contaminate about 25% of agricultural commodities globally. Mycotoxin contamination is a worldwide issue occurring in both tropical and temperate regions of the world. Mycotoxigenic fungi colonize cereals in the field and after harvest; thus, they harbor a mixture of many toxins. Crops when kept for

storage are also prone to fungal attack and may be polluted with mycotoxins during storage. Major food crops being infected by fungi and then intoxicated by mycotoxins include cocoa, coffee, cereals, oil seeds, spices, nuts, dried fruit, dried peas, beans, and fruits. The production of mycotoxins also depends on environmental factors during plant growth and then on the storage conditions of food (Fiers et al. 2013; Ameye et al. 2015). Mycotoxins can exhibit acute and chronic toxicity, mutagenic, and teratogenic effects. Humans may encounter severe health hazards or high mortality rates in countries with poor management programs. Toxic effects of mycotoxins depends on the nature of mycotoxins and their mode of action ranging from deterioration of the liver or kidney function and interference with protein synthesis leading to extreme immunodeficiency. Some mycotoxins are neurotoxic, and higher doses can lead to brain damage and death.

12.2 Origin and Chemical Nature of Mycotoxins

Mycotoxins are fungal metabolic compounds produced secondarily, capable of causing disease and death in humans and other animals. During ancient times, many major epidemics have been observed in humans and animals due to mycotoxin intoxication. Alimentary toxic aleukia (ATA) and ergotism are examples of dreadful mycotoxicosis instances that resulted in the death of thousands of people in Europe and Russia.

Mycotoxicosis is the term used to describe the toxic effects caused by mycotoxins. The toxic effects of mycotoxins depend on the duration of the exposure, health, age, and sex of the exposed individual. On the other hand, many factors like alcohol abuse, vitamin deficiency, and dietary status can also effect the severity of mycotoxin poisoning. Mycotoxins are manufactured from some general metabolic compounds and through a channel of various pathways (Bennett and Bentley 1989). The chemical nature of mycotoxins varies from alkaloids, sesquiterpenes, polyketides, derivatives of phenylalanine, and macrocyclic acid lactones (Ibrahim and Menkovska 2019). A wide variety of mycotoxins are known today, but most concerns are those causing severe health risk to both human and animals. They also impact nutrition and food security due to lack of access to safety and healthy foods (Bryden 2012).

12.3 The Mycotoxins

Filamentous fungi are common in the environment and can produce thousands of toxic compounds. However, mycotoxins produced by fungi are important as they are toxic at low concentration.

Exposure to mycotoxins in diet can cause vomiting, abdominal cramps, pulmonary edema, convulsions, coma, and death. *Aspergillus*, *Penicillium*, *Fusarium*, and *Claviceps* are the common species that produce more important toxins. From

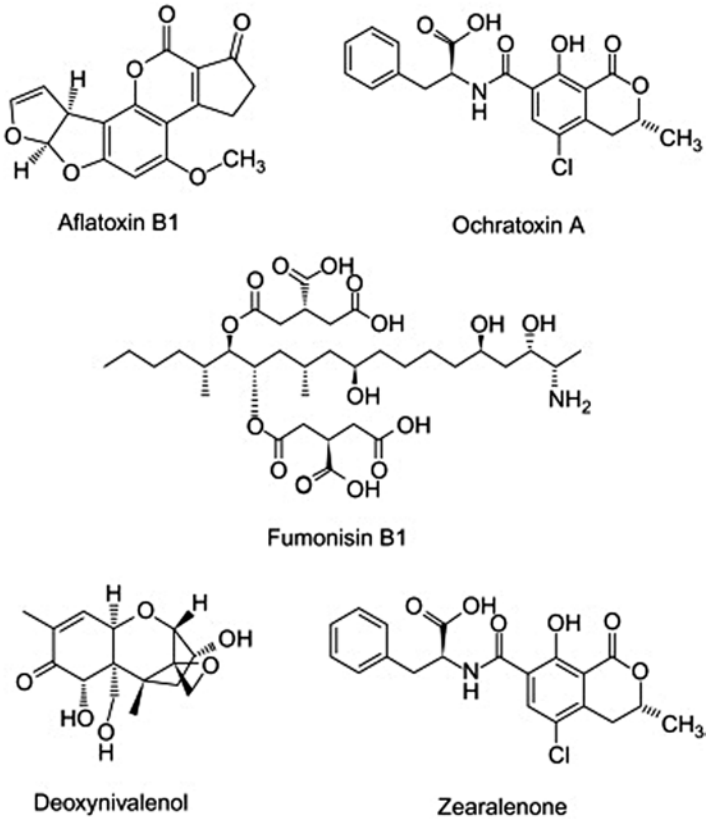

Fig. 12.1 Common types of mycotoxins (Source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC164220/)

toxicity and clinical manifestations point of view, the mycotoxins of foremost significance are aflatoxins (AFs), ochratoxin A (OTA), deoxynivalenol (DON), nivalenol (NIV), fumonisin (FUM), ergot alkaloids, zearalenone, T-2 toxin, and patulin (CAST 2003). The chemical nature and toxic impacts of different mycotoxins are explained below in Fig. 12.1.

12.3.1 Aflatoxins and Types of Aflatoxins

Aflatoxins are widely spread in food and feed supply chains. They are toxic chemicals produced by different species of *Aspergillus*, especially from *A. flavus* and *A. parasiticus* (Cotty and Jaime-Garcia 2007). Fungi-producing aflatoxins have been found in corn, peanuts, peanut products, cotton seeds, peppers, rice, sunflower

seeds, pumpkin seeds, and tree nuts. Contamination of aflatoxins is most common in countries with warm and humid climates like Africa, Asia, and South America and in temperate areas of Europe and North America. When agriculture crops contaminated with mycotoxins are used as green produce in foods and processing of animal feed, it results in contamination of final food products implicating severe health hazards to both humans and animals.

There are about fourteen chemical structures of aflatoxins being produced as secondary metabolites by *Aspergillus*, and the major groups of aflatoxins are aflatoxins B1, B2, G1, G2, M1, and M2. The B-type aflatoxins have distinct cyclopentane ring. These compounds have a blue fluorescence under long wavelength of UV. Aflatoxin B1 is the most toxic and potent carcinogen found to be correlated with hepatotoxicity and liver cancer. On the other hand, aflatoxin B1 has the ability to penetrate through the skin and cause health risk (Boonen et al. 2012). G-type aflatoxins have a xanthone ring instead of the cyclopentane. These compounds produce green fluorescence under UV. Other members of the aflatoxin family are originally isolated from bovine milk. These include M1 and M2 which are hydroxylation products of AFB1 and AFB2, respectively (Songsiriritthigul et al. 2010).

Poultry and farm animals fed on aflatoxin-contaminated feed produce contaminated meat, eggs, milk, and milk products. Human intake of these aflatoxin-contaminated products may result in liver damage and cancer. Children are more prone to develop toxicity to aflatoxin contamination, whereas adults are affected when doses exceed a certain amount (Gong et al. 2004). Aflatoxins have been found to be associated with changes in reproductive structures and hence the reproductive potential of human males (Kasturiratne et al. 2008). In food and animal feed, acceptable aflatoxin levels ranged from 20 to 300 ppm to prevent toxicity from a higher dose of aflatoxins (Stoloff et al. 1991). Permissible levels of mycotoxins in different food commodities as given by the FDA (Food and Drug Administration) are provided in Table 12.1.

Table 12.1 FDA regulatory guidance for mycotoxins in food and food commodities for human and animal use

Sr. no	Intended use	Food or food commodities	Permissible level of aflatoxins
1	Human consumption	Milk	0.5ppb
2	Human consumption	Foods, peanuts, peanut products, and nuts	20ppb
3	Immature animals	Animal feed, peanut products, and corn	20ppb
4	Dairy animals	Corn, animal feed and ingredients	20ppb
5	Breeding cattle and mature poultry	Corn and peanut products	100ppb
6	Beef, cattle, and poultry, regardless of the status of age or breeding	Corn and peanut products	300ppb

12.3.2 Ochratoxins

Ochratoxins are a group of compounds produced by a number of fungi like *Aspergillus* and *Penicillium* species, particularly *Aspergillus ochraceus* and *Penicillium cyclopium*. There are three types of ochratoxins, namely, A, B, and C. All types of ochratoxin have same basic structure, but R side chains may be variable. Ochratoxin A (OTA) is the most toxic and commonly detected as compared with other types of ochratoxins. *A. ochraceus*, *Aspergillus carbonarius*, and *Penicillium verrucosum* are major producers of ochratoxin A (Hassan and Mathesius 2012). These fungi are widespread in nature, as they can survive in a wide range of conditions (temperature, substrate, pH, and moisture). *A. ochraceus* is widespread in tropical regions, while *P. verrucosum* dominate temperate regions like Europe, Canada, and South America (Ruan et al. 1995). OTA are common contaminants of grains such as corn, oats, barley, rye, and wheat, whereas contamination of other plant products like coffee beans, nuts, spices, olives, beans, grapes, and figs has also been reported (Khan et al. 2003; Turra and Di Pietro 2015).

Investigations on the chemical structure of ochratoxin A revealed that it is a pentaketide derived by coupling of dihydrocoumarins family with β-phenylalanine. It has been found to be associated with contamination of water and house heating ducts, hence responsible for environmental and health hazards for human and animals (Hope and Hope 2012). Ochratoxin A can be absorbed by human and animal bodies on ingesting food and animal feed contaminated with ochratoxin A. After ingestion through food, it can be detected in host tissues, blood, organs, and breast milk of human and animals. It can cause renal tumors and nephrotoxicity (Bui-Klimke and Wu 2015).

Ochratoxin A is a stable molecule. It is fat soluble and cannot be readily excreted; hence, its uptake means its deposition in tissues of infected organisms which is directly proportional to the uptake of ochratoxin A. In animals, the main reason for ochratoxin A contamination is feeding on mold-contaminated fodder.

12.3.3 Fumonisins

Fumonisins (Fm) are toxic secondary metabolites produced by *Fusarium verticillioides*, *Fusarium proliferatum*, and some other Fusaria. Fungi producing fumonisins are found in grains, such as rice, sorghum, etc. *F. verticillioides* and *F. proliferatum* cause corn disease, namely, fusarium ear rot (Parsons and Munkvold 2012). More than 28 fumonisins have been isolated and are classified into four groups (A, B, C, and P). Fumonisin B1 (FB1) is the most abundant toxin contributing 70–80% to the total fumonisin group.

The chemical structure of fumonisin indicated their polyketide nature. Fumonisins consist of a 20-carbon aliphatic chain with two side chains which are linked to ester and hydrophilic in nature. Thus, they resemble sphingosine that is an essential

phospholipid in cell membranes. Gelderblom and coworkers were the first persons to isolate fumonisin B1 and fumonisin B2 from cultures of *F. verticillioides* (Gelderblom et al. 1988). The discovery of fumonisins go back to late 1980s where it is linked with many years of study on the disease known as equine leucoencephalomalacia (ELEM). Equine leukoencephalomalacia (ELEM) is commonly known as "moldy corn poisoning." It is a disease of the central nervous system affecting horses, mules, and donkeys with symptoms of blindness staggering, drowsiness, and liquification of brain tissues (Wilson et al. 1990). Disease is linked with feeding animals on moldy corns for a duration of several days to weeks.

Mycotoxin fumonisins specially produced by two species of *Fusarium*, that is, *F. verticillioides* and *F. proliferatum*, can cause esophageal cancer in human. Incidence of high rates of human esophageal cancer associated with fumonisins has been reported from China, Southern Africa, and Italy (Li et al. 1980; Marasas 1996; Franceschi et al. 1990). In other experimental studies, fumonisins were found to be involved in the inhibition of cell growth and induction of apoptosis *in vitro* (Tolleson et al. 1996). As per the directions of Food and Drug Administration (FDA), the permissible limit of fumonisins in human food should not exceed 4ppm/kg, whereas in animal feed, the level of fumonisin should not be more than 5–100 ppm/kg depending upon different types of farm animals (FDA 2001). This level can be achieved by good farming practices and better control of fungal growth.

12.3.4 Trichothecenes (TCTCS)

The term TCTCs is derived from trichothecin, the first isolated compound in this group. Many species of *Fusarium* produce TCTCs when infects corn, wheat, barley, and rice. TCTCs are also produced by fungi such as *Myrothecium*, *Trichoderma*, *Trichothecium*, *Cephalosporium*, *Verticimonosporium*, *and Stachybotrys*. Toxicogenic *Stachybotrys chartarum* can proliferate in humid storage environment and thus can cause environmental health hazard for residents (Hardin et al. 2003).

The Trichothecene family has been classified into A, B, C, and D types. All of the types have common sesquiterpene nucleus with epoxide ring and side chains of hydroxyl, methyl, or acetyl. All the types of trichothecenes are very stable and survive during various processes like milling or cooking and during storage of finished products (Widestrand and Pettersson 2011). Types A and B of trichothecenes are of utmost concern for consideration as causing harmful effects to both humans and animals with type A being more hazardous than type B. Subclasses of type A trichothecenes are Don, 3-ADon, 15-ADon, Niv, T-2, HT-2, and 4, 15 Das. These subclasses have same trichothecene nucleus but are varied in side chains. On the basis of toxicity, of the type A subclasses, T-2 trichothecene is the most toxic and at a concentration of 1 mg/kg body weight can inhibit translation in eukaryotic cells, thus leading to lethality (Ueno 1984). Dermal exposure to subclass T-2 trichothecene can initiate skin burning pain, redness, and appearance of blisters. Oral ingestion of T-2 trichothecene can cause vomiting, diarrhea, nasal irritation, and cough.

Table 12.2 Toxic effects and permissible levels of most toxic groups of trichothecenes

Toxic groups of trichothecenes	Subgroups of most toxic trichothecenes	Toxicogenic fungi	Toxic effects	Permissible level
Trichothecenes Type A	T2 HT2	*Fusarium langsethiae*, *Fusarium poae*, *Fusarium sporotrichioides*, *Fusarium equiseti*, and *Fusarium acumninatum*	Growth retardation, myelotoxicity, hematotoxicity, necrotic lesions on contact sites	100 ng/kg b.w./day
Trichothecenes Type B	Nivalenol (NIV), DON 3-ADon 15-ADon Fusarenon-X	*Fusarium graminearum* and *Fusarium culmorum*	Vomiting, hemorrhagic diarrhea, anorexia, suppression of body weight gain, hepatotoxicity, dermatological problems, and altered nutritional efficacy	1μg/Kg b.w/day to 1 mg/kg b.w./day for various derivatives

It can also affect vision, leading to blurred vision (Adhikari et al. 2017). Due to its high toxicity, this toxin is also produced by fungal fermentation and can possibly be used as biological warfare agent (Venkataramana et al. 2014).

Trichothecene (type B) is further classified into deoxynivalenol (Don), nivalenol, Fusarenon-X, and trichothecin. All have the same basic structure but vary in their side chains. The most frequently found toxin from type B trichothecene is the deoxynivalenol, also known as vomitoxin, due to the its ability to induce vomiting episodes when ingested. *F. graminearum* and *F. culmorusis* are the main producers of deoxynivalenol. They are plant pathogens causing fusarium corn blight in corn and fusarium head blight in wheat (Kim et al. 2016). Mycotoxicoses caused by trichothecenes affect many organs including the gastrointestinal tract and hematopoietic, cardiovascular, immune, and hepatobiliary systems. Initially, they can inhibit protein synthesis by binding with eukaryotic ribosomes. On the other hand, they can induce toxicity by deregulation of calcium homeostasis, impairing membrane functions and thus altering intercellular interactions. Higher doses of trichothecenes can cause rapid leukocyte apoptosis, leading to immunosuppression (Ueno 1983). They are also associated with reduced growth rate due to feed refusal and lost reproductive potential (Table 12.2).

12.3.5 Zearalenone (ZE)

A variety of Fusarium species, for example, *F. graminearum*, *F. culmorum*, *F. cerealis*, *F. equiseti*, *F. crookwellense*, and *F. semitectum*can, produce zearalenone (ZE). These species of *Fusarium* are common inhabitants of soil and are also known as

plant pathogens. High moisture contents and low temperature favor the growth of *Fusarium* species and hence production of zearalenone (Bennett and Klich 2003). ZE is resistant to high temperature treatment and can be detected in various cereal crops like maize, barley, rice, oats, and sorghum (Tanaka et al. 1988).

The chemical structure of Zearalenone is a macrocyclic β-resorcylic acid lactone, mimicking the reproductive hormone estrogen (Shier et al. 2001). This structural similarity to estrogen may cause early puberty in individuals. ZE binds with estrogen receptor and stimulates protein synthesis. Therefore, it is called phytoestrogen due to its hyperestrogenic effects and premature onset of puberty in female animals (Collins et al. 2006). ZE can also interact with immune system, resulting in immunosuppression (Berek et al. 2001). Zearalenone and its analogues can indicate clinical manifestations in both animals and human with major symptoms of enlarged uterus and mammary glands, swelling of vulva and vagina, and abortion in some cases. As zearalenone is heat stable and can withstand food processing like milling, grinding, heating, and cooking, its presence in food and food commodities should be controlled. As per FDA and WHO the maximum acceptable daily intake level of zearalenone to human and animal should be below 0.5 μg/kg body weight (Zinedine et al. 2007).

12.3.6 Patulin

Various species of *Penicillium*, *Aspergillus*, and *Byssochlamys* can produce a toxic metabolite named patulin (Ozsoy et al. 2008; Puel et al. 2010). *Penicillium expansum* is a famous patulin-producing species that is commonly present in rotten apple. It is also known as blue mold and attacks pear, cherry, grapes, and oranges. Chemically, patulin is a water-soluble lactone and is classified as polyketide. It was initially isolated in the 1940s as a broad-spectrum antifungal compound. It is known by different names like clavacin, expansin, clavatin, and gigantic acid as it was co-discovered by various groups who gave them different names (Goyal et al. 2017).

Patulin can cause DNA damage and is known as immunotoxic, genotoxic, carcinogenic, neurotoxic, and teratogenic. It can affect cells by formation of free radicals, leading to caspase-3 activation, leading to apoptosis (Saxena et al. 2009). Due to associated health risks, FDA regulated the patulin levels as 50 μg/kg in all squashes and 25 μg/kg for natural unprocessed apples, and it should not exceed 10 μg/kg in children's apple food products (EC 2006; Unusan 2019).

12.3.7 Ergot toxin

Outbreak of ergotism was noticed earlier in Middle Ages and France. Ergotism was then called St. Anthony's fire due to the burning sensation felt in limbs. It is caused by eating grains of rye or wheat contaminated with ergotamine, that is, a mycotoxin

produced by fungus *Claviceps purpurea*. Ergotamine causes vasoconstriction. This mycotoxin is extremely toxic. In recent years, different studies reported its toxic effect on human including hallucinations, gangrene, and even loss of limbs in humans or hooves in cattle (Klotz 2015). These toxic effects are induced by antagonism of neurotransmitters, like dopamine, norepinephrine, and serotonin, resulting in long-term vasoconstriction, leading to reduction of blood flow and related side effects. Ergot alkaloids have a number of applications in medicine from promoting labor pain, reducing uterine hemorrhage to treating migraines and endocrine disorders like parkinsonism (De Groot et al. 1998; Burn 2000; Crosignani 2006).

12.3.8 Sterigmatocystin

Sterigmatocystin (STE) is synthesized by many genera of fungi including *Aspergillus*, *Chaetomium*, *Bipolaris*, *Emericellai*, *Podospora*, *Fusarium*, *Farrowia*, *Humicola*, *Moelleriella*, *Monocillium*, and *Eurotium* (Rank et al. 2011). It was first time isolated in 1954 from cultures of *Aspergillus versicolor* (Castillo-Ureuta et al., 2011). STE is an antecedent compound of aflatoxin B1 (AFB1), and there is similarity between chemical structures and properties of both STE and AFB1. STE also exhibits hepatotoxic and carcinogenic effects like AFB1. STE is known to cause several toxic effects by interacting with the cell cycle, leading to DNA damage and cell cycle arrest. It can also induce apoptosis and hence cell death (Cui et al. 2017).

12.3.9 Nitropropionic acid (NPA)

A. flavus, *A. oryzae*, and *A. wentii* produce nitropropionic acid, which causes fatal food poisoning in human, congestion of liver and lungs, convulsion, and apnea. NPA can cause poisoning of livestock when they are fed on plants contaminated with NPA (Johnson et al. 2000). Consumption of contaminated foodstuffs can also cause toxicity in human. Even low doses of NPA can lead to acute encephalopathy and dystonia (Liu et al. 1992).

12.4 Other Mycotoxins

Penicillium also produces many other less common mycotoxins such as cyclochlorotine, rugulosin (RS), and luteoskyrin (LS). These toxins mainly affect the liver. Some other toxins produced by *Penicillium* are penicillic acid (PA), citrinin (CT), xanthomegnin, citreoviridin, and cyclopiazonic acid (CPA). *Alternaria* species also produce various toxins including alternariol, alternariol monomethyl ether (AME),

altertoxin I, tenuazonic acid, alternaric acid, dehydroaltenusin, altenusin, and alteriusol that contaminate common edible items such as vegetables, fruits, etc.

12.5 Detection of Mycotoxins

To minimize the exposure of human beings and livestock to mycotoxins, efforts should be directed to monitor and control the level of mycotoxins in foodstuff. Various countries have launched surveillance programs for the detection of mycotoxins to reduce their consumption risk.

Various techniques have been used for rapid detection of mycotoxins as a single method cannot serve the purpose due to differences in chemical nature, molecular mass, and functional groups of mycotoxins.

12.5.1 Traditional Techniques for Detection of Mycotoxins

Various chromatographic techniques are being used for detection and quantification of mycotoxins from cereals. Thin-layer chromatography (TLC), ultraviolet coupled with high-performance liquid chromatography, gas chromatography–mass spectrometry, and fluorescence are some of common techniques that are used for detection of mycotoxins. In addition, immunometric assays like ELISAs and membrane-based immunoassays are also commonly used to detect the presence of mycotoxins. TLC method is simple and cost-effective for detection of mycotoxins, but it has low sensitivity and accuracy. The limited length of TLC plate and the effect of temperature and humidity on separation of mycotoxins are some other limitations of TLC method; hence, modern methods involving quantification of mycotoxins are preferred. Liquid chromatography coupled with mass spectrum and fluorescence detectors are benchmark methods to detect mycotoxins (Cirlini et al. 2012). Due to ion suppression and matrix effects, LC-MS can give unsatisfactory results for the quantification of mycotoxins. In such cases, tandem mass spectrometry is preferred over fluorescence due to its ability to identify both nonfluorescent and fluorescent toxins.

Immunological assays, like ELISA, gained popularity for the detection of mycotoxins as they can directly be applied and no cleanup procedure is required. This method provides rapid and economical measurements, but at low concentration, it lacks precision. Other drawbacks in the method are time consumption, requirement of specialist plate reader, and inability to be used for field testing. Another immunochromatographic method is lateral flow strip assay. Antigen–antibody reactions are also used for quick analysis of mycotoxins with high specificity and sensitivity. This assay has been developed on commercial basis for the detection of many mycotoxins like DON and aflatoxins (Xu et al. 2010).

12.5.2 New Methods for Detection and Quantification of Mycotoxins

With the advancement in technology, various detection technologies have been developed for the detection and quantification of mycotoxins in recent years. Some of these techniques are ultrafast liquid chromatography connected with tandem mass spectrometry (UFLC-MS/MS), fluorescence polarization immunoassay, nanoparticle-based methods of detection, and implementation of chip-based method for detection of mycotoxins in foods. Other techniques such as biosensor and capillary electrophoresis are in progress. The presence of mycotoxicogenic fungi in food can also be detected by PCR. In short, a number of sensitive techniques are available for the detection of mycotoxins, but the selection of method should be based on objective of detection, sample size, nature of sample, and facilities available in laboratory (Singh and Mehta 2020).

12.5.3 Management of Mycotoxin Contamination

There are different ways which are developed for management of mycotoxin contamination in crops. These methods are given below.

12.5.4 Control of Mycotoxin Production

Preharvest control involves growing fungus-resistant crops, crop rotation with resistant varieties, control of insect pests using registered insecticides, and use of atoxigenic biocompetitives (such as control of aflatoxin contamination in crops by using native *A. flavus* strains which compete with toxin-producing strains) (Magan et al. 1984). Humidity and temperature have great influence on production of mycotoxins by toxicogenic fungi. Storage practices also play important role in the production of mycotoxins; hence, environmental factors like temperature, moisture level, and humidity of warehouses play important role in mycotoxin production.

12.5.5 Removal of Secreted Mycotoxins from Food

Secreted mycotoxins in food and feed can be eliminated by a variety of ways such as physical separation, filtration, and solvent extraction. Physical separation includes removing mold damaged seed and mold-damaged kernel by air blowing and density and floatation separation; that is, depending on the density of mycotoxins, they float and hence separated. Moreover, filtration involves using activated charcoal, clays,

and filter pads on which mycotoxins are adsorbed and hence separated. Moreover, solvent extraction, drying, washing, milling, boiling, irradiation, microwave heating, and peeling are also used as methods to remove secreted mycotoxins (Shi et al. 2018; Sarrocco and Vannacci 2018).

12.5.6 Detoxification of Mycotoxins

Different physical, chemical and biological methods have been designed to inactivate mycotoxins in food crops and feed. Physical destruction includes processes like gamma irradiation (World Health Organization, Food irradiation 1988). Some chemicals are also suggested to inactivate mycotoxins from food. These chemicals include acids, bases, aldehydes, and oxidizing gases. Biological methods that are formulated to destroy mycotoxins include enzymatic digestion and fermentation. Various reports are available regarding the use of microorganisms like bacteria and yeast and to degrade mycotoxins in food (Ben Taheur et al. 2019; Xia et al. 2017; Wang et al. 2019). Detoxification by biological means is considered as efficient approach as fewer and nontoxic end products are obtained. In vitro studies involving the use of microbial strains for detoxification produced significant results.

12.5.7 Elimination of Mycotoxins by Food Processing

Mycotoxins are usually not destroyed by cooking, but some mycotoxins may be inactivated by other types of food processing. Processing techniques cannot completely destroy the mycotoxins but can reduce their concentration (Neme and Mohammed 2017). Softening can be used to reduce the level of mycotoxins in food commodities as fungi accumulate on the surface of the granules. Although mycotoxins are compounds stable at higher temperature, still their concentrations can be reduced by using frying and baking methods at above 100°C. Similarly, under certain conditions, fumonisin B1 is reduced by sugars such as fructose to lose its hepatocarcinogenicity.

12.5.8 Dietary Modifications

Metabolism, distribution, and adsorption of mycotoxin are greatly affected by dietary modifications. For example, carcinogenic effects of AFB1 are inhibited by ascorbic acid and green tea. Similarly, toxic effects of ochratoxin A and fumonisin B1 are inhibited by vitamin C and vitamin E (Atanda et al. 2013, Karlovsky et al. 2016). Mycotoxin binders can be used that inhibit the absorption of mycotoxins by binding to mycotoxins. They do not allow mycotoxins to enter into the bloodstream

from the intestine. Commonly used adsorbent materials are activated carbon, complex nondigestible carbohydrates, aluminosilicates, and cholesterol. Although dietary modifications can reduce the risk of mycotoxins, further studies are required to ensure food safety.

12.6 Toxicology

Mycotoxins are known to cause several kinds of acute and chronic illnesses in humans and animals (Beardall and Miller 1994). Toxic effects of mycotoxin exposure in humans are associated with ingestion of contaminated food and water and inhalation of aerosols (Babič et al. 2017; Kumar et al. 2017; Viegas et al. 2017). Since a substantial number of agricultural products are contaminated throughout the world, food ingestion is found to be the main route of exposure, especially in humans, although inhalation of aerosolized particles is a conceivably important route of exposure principally in certain working areas, such as product processing plants, and spaces where there are chances of high airborne concentration (Hooper et al. 2009; Ferri et al. 2017).

Comparable to all infectious agents, mycotoxin exposure can result in a spectrum of medical disorders, affecting organ systems and superficial skin and inducing allergic reactions such as asthma, sinusitis, pneumonitis, and hypersensitivities (Bossou et al. 2017). Mycotoxin exposure can also result in conditions such as vomiting, abdominal cramps, edema, convulsions, and even death. Long-term toxic effects of mycotoxins can cause physiologic decompensation for an individual such as cancer and immune deficiency (CAST 2003; Lewis et al. 2005).

The mycotoxins of foremost importance are "AFs, ochratoxin A (OTA), deoxynivalenol (DON), fumonisins (FUM), nivalenol (NIV), ergot alkaloids, T-2 toxin, patulin and zearalenone" arranged in the order of severity of disease they cause (CAST 2003). Co-occurrence of mycotoxins has also been observed. These mycotoxins sometimes are exposed in combinations, for instance, AFs and FUMB1, and vomitoxin and zearalenone are found to co-occur in the same corn. When more than one mycotoxins are consumed in combination, response to such exposure can be classified into following categories: (i) additive, when the interactive effect can be measured by individual consideration of each mycotoxin; (ii) antagonist, if the effect is lower than the anticipated from each mycotoxin individually; or (iii) synergic, if the response of one toxin is augmented by the presence of second toxin; synergistic effects are more pronounced than additive and antagonist (Paterson and Lima 2010; Gil-Serna et al. 2014).

Potential toxicological effects of mycotoxins are acute, chronic, mutagenic, hemorrhagic, hepatotoxic, nephrotoxic, and neurotoxic effects on multiple systems, leading to death sometimes. These toxicological effects happen due to interference in the vital processes like protein synthesis and DNA replication causing necrosis,

lung infection, and weakened immunity and can also result in mutagenic and teratogenic effects (Omotayo et al. 2019).

12.6.1 Hepatic Effects

The liver is known to be a biologically active organ in performing vital activities: metabolism, excretion, and detoxification (Surai 2005, Shaker et al. 2010). The liver is known to be the foremost target organ for mycotoxin toxicity and carcinogenicity, especially aflatoxins. Aflatoxins perform their mechanism of action by interrupting the immune function. Aflatoxins interfere with nucleic acids and protein synthesis, causing toxicity in targeted organs (Afsah-Hejri et al. 2013). When mycotoxins are absorbed in the digestive tract, they are transferred to the liver, thereby causing damage to the liver (Dalezios et al. 1973).

Hepatocellular carcinoma is considered to be the most commonly occurring disease and is the fourth leading cause of deaths worldwide (Eaton and Groopman 1994). It was estimated that there is a high correlation between the incidence of hepatocellular carcinoma and the presence of aflatoxin B1 (Henry et al. 2001). Notably, it is reported that aflatoxin consumption is responsible for 530% of liver cancer (Liu and Wu 2010). Incidence of carcinoma of liver cancer is estimated to be around 40 percent. Approximately 80% carcinoma cases are reported from developing countries with the highest outbreak in Africa, approximately 40% cases and 55 % from China (Liu and Wu 2010; Chhonker et al. 2018). In this regard, as the level of aflatoxin intake is increased, the incidence of liver cancer is logarithmically elevated (Henry et al. 2001). Several studies have suggested there is synergistic effect of aflatoxins and hepatitis B and C virus in the etiology of the liver cancer (Wu and Santella 2012; Palliyaguru and Wu 2013).

Furthermore, several studies have demonstrated that mycotoxin exposure causes changes in hepatic histopathology, including bile duct proliferation, periductal fibrosis, and cholestasis (Javed et al. 1993). The effects of mycotoxins (aflatoxins and ochratoxins) on hepatic histopathology have been studied in broilers by Bakeer et al. (2013). From that experiment, it was found that aflatoxin exposure amplified Kupffer cell activation, sinusoidal dilation, and periacinar hepatic necrosis and hepatocellular vacuolations. Additionally, Ortatatli et al. (2005) reported that if the concentration of aflatoxins in diet is around 100 ppb, they can cause hydropic degeneration and fatty vacuoles in hepatocytes. Also, Krishnamoorthy et al. (2007) demonstrated that exposure of T-2 toxin results in enlargement of the liver, hepatocyte necrosis, and hyperplasia of the bile duct.

Furthermore, ochratoxin A has been estimated to be teratogenic in experimental animals, where it interferes and inhibits hepatic mitochondrial transport systems and causes injury to the liver, and various studies suggest that OTA is excreted in milk of affected animals (Chhonker et al. 2018).

12.6.2 Neurotoxic Effect

Likewise, other organs mycotoxins induce etiology in neuronal tissue, but there are only few surveys reported for such toxicity. Among several mycotoxins, T-2 toxin, macrocyclic trichothecene, fumonisin B1 (FB1), and ochratoxin A (OTA) are considered to have the ability for causing neurotoxicity (Uetsuka 2011). During neurotoxicity, immune responses damage neurons, and the overall CNS damage is amplified by astrocytes and endothelial cells (Karunasena et al. 2010). Low concentration of T-2 toxin can cause alterations in the metabolism of brain biogenic monoamines in experimental model, and intake of T-2 toxin results in altered permeability for amino acids. T-2 toxin if reaches the fetal brain causes fetal death and fetotoxicity primarily in the CNS. Study suggests that T-2 toxin-induced effects may be the outcome of oxidative stress (Uetsuka 2011).

Ergot exposure can induce convulsions and hallucinations. Neurologic effects can be induced by volatile organic chemicals (VOCs). Kodua poisoning is caused by cyclopiazonic acid and 3-nitropropionic acid produced by *Arthrinium* species and *Penicillium* and *Aspergillus* species, respectively. Symptoms include dystonia, convulsion, and carpopedal spasm.

Mycotoxins produced by *Penicillium* and *Aspergillus* species are "tremorgenic" and known to cause tremors, ataxia, and convulsions (Fung and Clark 2004). FB1 has the potential to cause cerebral cortex neuronal degenerations, concurrent with inhibition of ceramide synthesis. OTA induces acute deficiency of striatal dopamine and its metabolites, followed by substantia nigra, striatum, and hippocampus neuronal cell apoptosis (Uetsuka 2011).

12.6.3 Renal Toxicity

Long-term exposure to mycotoxins causes nephropathies and urinary tract tumors (Jahanian 2016). AFB1 is considered to be nephrotoxic because toxin targeting kidney induces various effects (Madhavan and Rao 1967; Akao et al. 1971), and in kidney, these mycotoxins reduced the rate of glomerular filtration, tubular reabsorption, and the tubular transport. But it increases the rate of excretion of Na and K and gamma-glutamyltransferase (Grosman et al. 1983). Renal cortex of albino rats demonstrated that AFB1 induces degeneration and necrotic changes and enlargement of glomeruli (Grosman et al.1983).

Various renal cell lines were used to demonstrate renal toxicity. The renal toxicity study established that cell multiplication was decreased in renal cell lines. Fetal kidney cells were reported to be more sensitive to the cytotoxic effect (Yoneyama et al. 1987). AFB1 and AFM1 toxicities were assessed on HEK293 cells and CD-1 mice. The two mycotoxins, individually or in combination, caused the formation of ROS, leading to kidney damage with a considerable decrease in L-proline and proline dehydrogenase (Li et al. 2018).

Occurrence of ochratoxin A in the serum in high levels indicates chronic nephropathy (Abid et al. 2003). Ochratoxin A binds to low molecular weight macromolecule in serum inducing nephrotoxic effects when accumulated in the kidney (Stojković et al. 1984; Ali and Abdu 2011), demonstrating ochratoxin A effects on rats' kidney. They reported that ochratoxin A treatment decreased kidney weight and increased the levels of serum urea and creatinine. Furthermore, animal study showed that ochratoxin A treatment induced proximal tubular atrophy and cortical interstitial fibrosis (Bayman and Baker 2006).

12.6.4 Effect on Gastrointestinal Tract

GI tract is the first physiological barrier against contaminated food products and the first target for mycotoxins too. When intestinal mucosa is contracted by such contaminants and toxins, they exert their deleterious effects on gastrointestinal tract (Pinton and Oswald 2014; Akbari et al. 2017). Ingestion of mold-contaminated food items and beverages and potential mycotoxins exposure produce symptoms such as nausea, vomiting, abdominal pain, and diarrhea. The mechanism of toxicity is associated with direct toxic effects on gastrointestinal mucosal surfaces. Mushroom toxicity causes similar toxic effects on GIT (Fung and Clark 2004). Mycotoxins, primarily aflatoxins, ochratoxin, and deoxynivalenol (DON), have been demonstrated to alter intestinal permeability in different species (Moldal et al. 2018).

The health and performance of an individual are correlated with intestinal microbiota. Intestinal microflora competitively inhibits colonization of the intestinal epithelium by foreign pathogens modulating the gut-associated lymphoid tissue (GALT). Recent study revealed that ochratoxin A (OTA) occurrence in the colon significantly decreased concentrations of acetic, butyric, and total short-chain fatty acid (SCFA), indicating that OTA can alter composition and metabolism of the colonic microflora (Broom 2015).

There is a correlation between the intestine and ingested mycotoxins and their deleterious effects in an individual. Mycotoxins exert negative effect on intestinal health, for instance, declined intestinal cell viability and decreased concentrations of short-chain fatty acid (SCFA). Beneficial bacteria are eliminated, and increased expression of genes is increased related to inflammatory response and counteracting oxidative stress. These negative effects will lead to recurrent intestinal infections and impaired digestion process and absorption of nutrients (Liew and Mohd-Redzwan 2018).

12.6.5 Mutagenic Effects

Mycotoxins are considered to be mutagenic, carcinogenic, and teratogenic because they interact with nucleic acid (DNA) and other macromolecules (Paterson 2008). Mutagenic effects exerted by mycotoxins can be direct or indirect; these can either

change bases (direct) or inhibit enzymes (indirect) involved in stabilization of nucleic acids (Paterson 2008; Paterson and Lima 2009). Carcinogenic mycotoxins include AFs, sterigmatocystin, OTA, FUMs, zearalenone, citrinin, luteoskyrin, patulin, and penicillic acid. All of these function by damaging DNA except for FUMs, which interferes in signal transduction pathways (Gacem et al. 2020).

High levels of ROS resulted in neuronal stress, when neuronal cell line (Neuro2a) was exposed with OTA. Furthermore, other events also lead to mutagenic effects: mitochondrial membrane lost, DNA damage, and higher gene expression of neuronal biomarker inducing apoptotic cell death. In SH-SY5Y neuronal cells, OTA increased dose-dependent cytotoxicity levels with concurrent caspase-9 and caspase-3 activation in rat embryonic midbrain cells (So et al. 2014).

Co-occurrence of T-2 toxins and aflatoxin B1 makes them the strongest mutagens. Sehata et al studied the alterations in gene expression induced by T-2 toxin in the fetal brain of pregnant rats. T-2 toxin treatment upregulated gene expression for oxidative stress (heat shock protein) and apoptosis (caspase-2). In another study, it was reported that deoxynivalenol treatment (2501000 ng/mL) could cause an increase in interleukin-8 mRNA. It was indicated that the ochratoxin A treatment increased gene expression for apoptosis, inflammation, and oxidative stress in rat kidney (Jahanian 2016).

12.6.6 Other Effects

Since ZEA are present in the air, they are thought to cause pulmonary and cardiovascular toxicity. In one study, human bronchial epithelial cells (BEAS-2B) were treated with 40 mM ZEA; as a consequence, mycotoxin caused DNA damage, cell cycle arrest, and downregulation of inflammation (Ben Salem et al. 2017). Outcome of ZEA interaction with H9c2 cardiac cells caused oxidative stress (Sharma 1993).

The immune system is known to be an important defensive system against foreign pathogens and invaders (Pestka 2008). Specialized immune cells interact with each other to give off desired consequence (Turner et al. 2003). Mycotoxins either exert suppressive or stimulatory effect on immune system (Girish and Smith 2008). Previous study has reported that aflatoxin exposure induces immunosuppression, indicating that the susceptibility to infections is increased with AF intake. Girish and Smith (2008) found that immunosuppression is induced by several mechanisms, as depicted by the decreased antibody production, the delayed hypersensitivity response, the decreased bacterial clearance from systemic route, the declined lymphocyte proliferation, the suppression of macrophage phagocyte ability, and the changed CD4+/CD8+ ratio.

Aflatoxin B1 exerts their action on biomolecules such as DNA, changing their actions (Bhat et al. 2010). Mycotoxins always lead to inhibition of protein synthesis; consequently, they impair immune cell proliferation. But mycotoxins are also known to adversely affect the surface receptors of macrophages, neutrophils, and

lymphocytes; consequently, miscommunication between defense cells led to immunosuppression.

It has been also demonstrated that mycotoxins also cause suppression of humoral immunity. In this concern, ochratoxin A is known to suppress natural killer cell activity by inhibiting interferon production (So et al. 2014).

12.7 Mycotoxin Management and Degradation

Several factors influence mycotoxin production from respective fungal species such as temperature, moisture, existing nutrients, humidity, and some others (FAO 2002). Fungal growth and mycotoxin production can be prevented by employing good agricultural and manufacturing practices. Developing countries suffer more from mycotoxin presence in agricultural products, whereas developed countries have opted for modern technologies and good control (FAO 2002). The Hazard Analysis and Critical Control Point (HACCP) system also has significant role in mycotoxin prevention and management (Kabak et al. 2006; Stove 2013), though several strategies like good agricultural and manufacturing practices can prevent the mycotoxigenic fungal and mycotoxin development. However, once food has been contaminated with mycotoxins, postharvest detoxifying strategies are needed to manage contaminants in feed and food.

However, it is not possible to always avoid mycotoxin contamination during preharvest, postharvest, and storage, requiring detoxification of feed and food. Therefore, several detoxification processes are employed for prevention of mycotoxin exposure and the effects produced by them. Detoxification of mycotoxins in such cases can be accomplished by either removing or eliminating the contaminated products or inactivating the mycotoxins present in food or feed by physical, chemical, or biological methods (Beretta et al. 2000).

12.7.1 Physical Methods

Several physical strategies are employed for elimination and inactivation of mycotoxins in food commodities.

Sorting and Segregation Mycotoxins can be removed from food commodities by means of sorting and removal. It has been found that patulin levels are reduced up to 99% by sorting and segregation of rotten and poor-quality fruits or trimming of decayed sections of fruits (Scudamore and Banks 2004; Broggli et al. 2002). Fumonisin and aflatoxin contamination in corn can be reduced by sorting and segregation (Peraica et al. 2002).

Heat Treatment Many mycotoxins are heat stable so they are not easily destroyed within normal temperature (80–121 °C) range of food processing; boiling, frying, and pasteurization. Factors such as moisture content, ionic strength, and pH of food are known to affect the sensitivity of mycotoxins. Aflatoxins are degraded within temperatures range 237–306 °C. Aflatoxins can be decomposed when food commodities contain higher moisture content (Beretta et al. 2000).

Irradiation Radiation has been proven useful in control of aflatoxins, T-2 toxin, or deoxynivalenol in grains and was also found effective on OTA decontamination in poultry feed which can be achieved by UV radiation for one hour (Gul Ameer et al. 2016; Avantaggiato et al. 2004).

Filtering and Adsorption Mycotoxin adsorption decreases aflatoxin, patulin, ZEA, DON, and nivalenol residues by activated charcoal addition due to its porous nature (Liu et al. 2011; Magnoli et al. 2011). Mycotoxin adsorption by bentonite clay effectively eliminates aflatoxin B1 from aqueous environments, and it has been found that bentonite clay helped in removing aflatoxin M1 from milk (Venter 2014).

12.7.2 Chemical Methods

Several chemical agents have been proven to successfully decontaminate and inactivate mycotoxins and have been investigated for their effectiveness in mycotoxin decontamination, namely, bases, oxidizing agents, organic acids, and other agents.

Bases (Ammonia, Hydrated Oxide) Ammonization of grains helps mycotoxin control, preventing fungal growth and reducing aflatoxins, fumonisins, and OTA levels. However, this detoxification method is not acceptable for human food in the European Community (EC) (Peraica et al. 2002). Recently, a mixture of glycerol and calcium hydroxide was shown to have a powerful detoxification effect for mycotoxins. A mixture of 2% sodium bicarbonate solution and potassium carbonate reduces OTA contamination in coco shells (Federal Register 2003).

Oxidizing Agents (Hydrogen Peroxide, Ozone) Ozone has been approved for effective decontamination of mycotoxins (Agriopoulou et al. 2016). Ozone degraded patulin, aflatoxins, and zearalenone. The decontamination of aflatoxins AFB1, AFB2, AFG1, and AFG2 was achieved with ozone (Quintela et al. 2012).

Organic Acids Several organic acids successfully degraded ochratoxin OTA. Egg albumin efficiently reduced OTA levels without affecting total polyphenols (San'Ana et al. 2008).

12.7.3 Biological Methods

Various physical and chemical detoxification methods have been developed to control mycotoxin contamination and fungal growth. However, not all of them are not permitted due to their biosafety concerns and high cost.

There is a need to devise appropriate biological detoxification strategies for ensuring food safety (Walter et al. 2015; Petchkongkaew et al. 2008). Numerous bacteria, molds, and yeasts can biodegrade mycotoxins in food for human consumption.

Bacterial Strains Several scientists reported that *Bacillus* and *Brevibacterium* species in their interaction with mycotoxins can detoxify them. *Bacillus licheniformis* isolated from soybean removed OTA efficiently, with efficiency of 92% with 48 h treatment at 37 °C (Cho et al. 2010).

Bacillus natto and *Bacillus subtilis* were shown to remove zearalenone from liquid medium: up to 75% zearalenone could be degraded after incubation. In another study, was degraded by this *B. subtilis* strain interaction biodegraded up to 99% of zearalenone (Moss and Long 2002; Tinyiro et al. 2011). Recent studies have indicated probiotic potential of different Lactobacilli to degrade fungal toxins (Zada et al. 2021).

Yeast Strains Yeasts can efficiently inhibit mycotoxigenic fungal growth and to prevent mycotoxin synthesis. *Saccharomyces cerevisiae* decreased patulin contamination during fermentation of juices: patulin could be removed completely after 2 weeks' yeast fermentation (Gromadzka et al. 2009).

Molds In addition to bacteria and yeasts, molds can also biocontrol mycotoxins; molds such as *Aspergillus*, *Rhizopus*, and *Penicillium* spp. can also effectively detoxify mycotoxins. *Clonostachys rosea* effectively detoxify mycotoxins in cereals (De Felice et al. 2008). OTA accumulation and aspergillosis occurrence are inhibited by *Aureobasidium pullulans* and therefore used as a biocontrol agent in fruits or in wine grapes (De Felice et al. 2008).

12.8 Climate Change and Increased Mycotoxin Production

Climate change is an inevitable probability as assessed by prominent researchers. Conducive temperature and water activity are pivotal for fungal growth and production of noxious fungal metabolites. Climate change is depicted by three major factors: (i) temperature rise, (ii) increase in CO_2 concentration, and (iii) drought stress (Medina et al. 2016). The rise in global temperature will raise mycotoxin ratio in temperate regions, and food security in these countries may become prone to increased aflatoxin production. Preharvest fungal infection of crops may prevail, and the outcome may be increased mycotoxin production in the field. There may be

increased incidence of ochratoxin A, patulin, and *Fusarium* toxins. The European Food Safety Authority has reported that earlier ripening of crops in central and southern Europe will enhance pests and occurrence of diseases. Conventional fungal species may diminish in tropical regions; hence, mycotoxin production may decrease (Paterson and Lima 2010).

It has been suggested that climate change may induce a 1/3 of yield variability in major food commodities globally (Ray et al. 2015). It has been noted that Serbian maize was devoid of any aflatoxins during 2009–2011, but 69% maize was affected by aflatoxins in 2012 when temperature was increased (Kos et al. 2013). Dobolyi et al. (2013) have also observed similar findings in Hungary.

The estimates indicate increased atmospheric CO_2 concentration in the coming 25 years up to 350–400 versus 650–1200 ppm (Medina et al. 2016). CO_2 increase with elevated temperature and water stress condition will modify the growth of toxigenic fungi and pattern of mycotoxin production.

Studies are lacking in revealing the acclimatization ability of fungal species to climate change. The optimum temperature required for growth of toxigenic fungus differs from the temperature at which toxin is produced. The raised temperature may induce production of different toxin as indicated in a study when *Alternaria alternata* capable of producing alternariol (AOH), alternariol monomethyl ether (AME), and altenuene (AE) produced AOH at 21°C at 0.95aw but at higher temperature produced increased concentration of AME (Vaquera et al. 2017). Three-factor interaction was investigated by Medina et al. (2016) under elevated temperature, drought stress at 37 °C, and increased CO_2 concentrations (650 and 1000 ppm). Molecular studies related to aflatoxin gene expression also concluded same findings.

12.9 Future Prospects

The presence of these noxious contagions in food, feed, and the environment is of great concern due to their association with a multitude of detrimental health effects. The human population is more exposed to other contaminants including pesticides, heavy metals, and other pollutants. Recent studies have revealed their presence in human blood and urine (Arce-López et al. 2020). Humans are often concurrently exposed to heterogeneous mixtures of mycotoxins provoking a public health perspective. Actual exposure to mycotoxins based on food consumption is quite difficult to assess, and detection of mycotoxins bound to organic molecules has also become problematic. Climate change perspective urges for great concern on mycotoxin increase in environment and food commodities, ultimately affecting human health. These factors compel for managing the risk associated with mycotoxins and taking preventing measures to control the growth of mycotoxigenic fungi. Some novel approaches are need of time to combat the risk of increased mycotoxins in the environment to assure food safety.

12.10 Conclusion

Mycotoxin contamination is a worldwide problem as they are the most toxic and dangerous toxins linked with food safety. They have diverse chemical structures having various effects on human and animal health. They adversely affect the quality of agricultural products and are responsible for significant economic losses. Efforts should be made to control mycotoxin production at preharvest stage and detoxify them to minimize their exposure. Effects of climate change on mycotoxin production should also be studied in current scenario of elevated temperature, increased CO_2 concentration, and the expected drought in tropical region. There is a need to constantly monitor the quantity of mycotoxins in food commodities to cope with the demand for healthier foods.

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