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Review

Mycotoxin occurrence in grains and the role of postharvest management as a mitigation strategies. A review

Kumera Neme [a, b, *], Ali Mohammed [b]

[a] Department of Food Science and Nutrition, College of Agriculture, Wollega University, Box 38, Shambu, Ethiopia
[b] Department of Postharvest Management, College of Agriculture and Veterinary Medicine, Jimma University, Box 307, Jimma, Ethiopia

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ABSTRACT

Mycotoxins are poisonous compounds produced by certain species of fungi found in contaminated grain. There are five major groups of mycotoxins which can occur in grains: Aflatoxin, fumonisin, deoxynivalenol (DON), ochratoxin (OT), and zearalenone (ZEN). Their occurrence may start in the field, harvesting, handling, storage, and processing. DON, ZEN, and fumonisins may start to cause the grains at the field/or pre-harvest while aflatoxin and OT are mostly occurring during storage due to improper postharvest handling. Most of the grains susceptible to mycotoxins such as maize, peanut/groundnut, sorghum, millet, wheat, and rice were reviewed. The main postharvest factors for the cause of grain mycotoxin contamination are mechanical injury, insect infestation, time of harvesting, drying method, types of storage structure and conditions, handling and processing. Temperature, moisture and humidity are the main factors for the growth and development of mycotoxins. Developing countries especially African are more vulnerable for the causes due to lack of well-established infrastructures, regulations, and standards. Postharvest mitigation strategies are an important and cost-effective method to control the cause. The core grain postharvest interventions used as mitigating strategies of mycotoxin includes rapid and proper drying, postharvest insect control, proper transportation and packaging, good storage conditions, use of natural and chemical agents and irradiation. Grain processing such as sorting, cleaning, milling, fermentation, baking, roasting, flaking, nixtamalization and extrusion cooking are also reported to reduce mycotoxin concentration. In general, system approach to good manufacturing practice and HACCP based implementation are important to mitigate mycotoxins in grains.

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* Corresponding author. Department of Food Science and Nutrition, College of Agriculture, Wollega University, Box 38, Shambu, Ethiopia.
E-mail addresses: kumneme@gmail.com (K. Neme), alimhmd@yahoo.com (A. Mohammed).

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1. Introduction

Under certain environmental conditions, some fungal species that can infect grains, produce toxic byproducts called mycotoxins (Benbrook, 2005). Mycotoxins are poisonous compounds produced by certain species of fungi found in contaminated grain. Fungal infection and production of mycotoxins may start in the field, at harvesting, handling, storage, and processing. Critical factors for fungal postharvest infection and subsequent synthesis of mycotoxins include initial grain moisture content, timeliness of harvest, length of wet holding before drying, the amount of grain and foreign materials, the amount of grain dust, the type and quality of storage structures, grain temperature, the interstitial air relative humidity, headspace condensation, bulk grain moisture movement, and insect infestation (Channaiah & Maier, 2014).

The condition of grains especially during storage are the main factors for the growth of mycotoxins. Especially, the conditions like moisture and temperature are critical factors for determining the safety of stored grain. The main factors that favor fungal growth and mycotoxin biosynthesis in stored grain are high grain moisture (16–30%), warm grain temperature (25–32 °C), and high air RH (80–100%) (Shanahan, Brown, & Blunt, 2003).

Viewed globally, food safety is regularly compromised by the presence of mycotoxins occurring in grains (D'Mello, 2003). Mycotoxin problems in agricultural commodities confronting the food industry, scientists, and governments in both the developed and developing the world (Benbrook, 2005). There is a huge economic impact of mycotoxin infection in the world. Some of it may include loss of human and animal health and life, increased healthcare costs, reduced livestock production, disposal costs of contaminated foods and feeds, pre- and postharvest losses in crops, research investment, and regulatory programs aimed at reducing or excluding mycotoxins from end products (Zain, 2011).

Postharvest losses due to mycotoxins are an emerging issue of the globe where especially it is significantly influencing African countries. Worldwide, approximately 25% of food crops are affected by mycotoxins causing a loss of nearly 1 billion tons of foodstuff per year (Bryden, 2007; Channaiah, 2011). International Agency for Research on Cancer (IARC) reported an estimated 500 million of the poorest people in sub-Saharan Africa, Latin America, and Asia are exposed to mycotoxins at levels that substantially increase mortality and morbidity (Pitt et al., 2012; Wild, Miller, & Groopman, 2015, p. 9). Most developing countries are in the world's tropical zones and are subjected to monsoons and high temperature and humidity levels, which contribute to large postharvest crop losses (Wild et al., 2015, p. 9). So, effective mitigation strategies are vital for the world to control the huge effect of mycotoxins.

A lot of research are focusing on the mitigation strategies of mycotoxin due to their severity on human health risks (Bullerman & Bianchini, 2014; Jans, Pedrosa, Schatzmayr, Bertin, & Grenier, 2014; Munkvold, 2003, 2014; Ochieng, Okun, Runo, Njagi, & Murage, 2013; Wild et al., 2015, p. 9). It is the aim and need of every country to enhance the control strategy of food quality and safety. Control strategies are being developed around attempts to influence some of these conditions through the management of agricultural practices prior to and at harvest (Richard et al., 2003). Multidisciplinary integration of know-how and technology is required to address the broad requirements for reducing mycotoxins in agro-food chains (Logrieco & Visconti, 2014). Cost effective and safe treatment techniques to control mycotoxins entering the food chain are important. There are pre- and postharvest mitigation strategies of mycotoxin in grains. Postharvest management has a significant role in mitigation of mycotoxins through good management in grain food chains during harvesting, cleaning, drying, storage, and processing. Sanitation, screening, aeration and monitoring of stored grain are important good management practices during grain storage.

Control of moisture, temperature, and humidity to safe storage level is a key to mitigating mycotoxin in grains. Good postharvest and processing techniques and strategies to control mycotoxins begin with harvesting at grain moisture levels low enough to prevent fungal growth, or drying to such levels (Bullerman & Bianchini, 2014). Effective implementation of good manufacturing practices in grain elevators and hazard analysis at critical control points (HACCP) will reduce levels of mycotoxins in the food supply chain (Channaiah, 2011).

Research efforts to mitigate mycotoxin contamination in grain are focusing on breeding and genetic engineering for crop resistance, manipulation of agronomic practices, the use of biological control and proper postharvest management. Of these postharvest management options is perhaps the most promising and cost-effective method for management of mycotoxin contamination in grains. So, the aim is to review the common type of mycotoxins affecting grains, their occurrence and role of postharvest management as a mitigation strategy.

2. Mycotoxins and their occurrence in grains

Over 300 species of fungi produce byproducts called mycotoxins. Mycotoxins are a diverse and ubiquitous group of fungal compounds specifically associated with the precipitation of deleterious effects in humans and animals (D'Mello, 2003). They are toxic secondary metabolites produced by fungi that commonly called mold. The mycotoxins of major concern for human health are produced by three main genera of fungi: *Aspergillus* (produces aflatoxins and OTA), *Fusarium* (produces fumonisins, ZEN, and

trichothecenes), and *Penicillium* (produces OTA). The five major groups of mycotoxins are aflatoxin, fumonisin, DON, OT, and ZEN. Naturally occurring aflatoxin were classified as carcinogenic to humans (Group 1), OT and fumonisin were classified as possible carcinogens (Group 2) while trichothecenes and ZEN were not classified as human carcinogens (Group 3) (WHO-IARC, 1993; Zain, 2011).

Mycotoxins occur more frequently in areas with a hot and humid climate, favorable for the growth of molds, they can also be found in temperate zones. Fungi produce mycotoxins in response to stress caused by environmental extremes, shortage of food, or competition from other microorganisms (Benbrook, 2005). Most of the time more than two mycotoxins may occur together at the same time in grains. Aflatoxins, fumonisins, DON and ZEN may occur together in the same grain; many fungi produce several mycotoxins simultaneously, especially *Fusarium* species. For example, the study conducted in Nigeria revealed that aflatoxins and fumonisins co-occurred in about 65% of the maize grains with repeated additions of OTA, DON, ZEN and the emerging toxins (Adetunji et al., 2014). Co-occurrence of mycotoxins is of special concern, for instance, in the case of fumonisins (a potent cancer promoter) and aflatoxin (a potent human carcinogen) where a complimentary toxicity mechanism of action occurs (Bryden, 2007). The co-occurrence of deoxynivalenol and/or its conjugate (deoxynivalenol glucoside) with fusaric acid are additional risks for consumers of the grains because fusaric acid is known to increase deoxynivalenol toxicity several folds, and the conjugate is capable of hydrolyzing to its parent compound (Adetunji et al., 2014).

Mycotoxin contamination of crops can occur in the pre- and postharvest agricultural system due to inadequate agricultural practices (Wild et al., 2015, p. 9). The most commonly associated mycotoxins with cereal grains following pre- or postharvest contamination are displayed in Table 1. Field fungi are usually known with high requirements of water whereas storage mycotoxins require lower of humidity. Important field and storage mycotoxins are shown in Fig. 1.

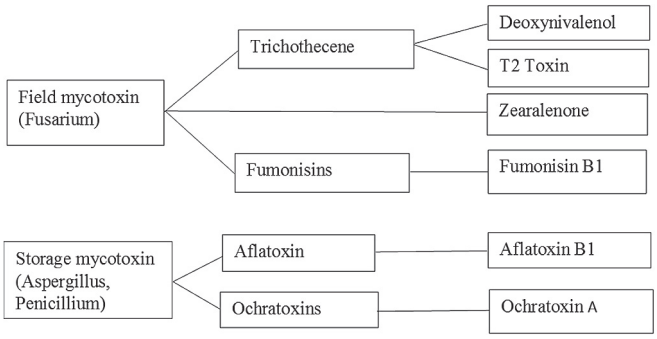

Fig. 1. Important mycotoxins occurrence in grains.

2.1. Aflatoxin

Aflatoxins are naturally occurring toxins produced by certain fungi, most importantly *Aspergillus flavus and Aspergillus parasiticus*. It is the most toxic mycotoxin and is among the most widely distributed and well known (Benbrook, 2005). Four main types of aflatoxins; B1, B2, G1 and G2 have been identified with B1 being the most toxic, carcinogenic and most prevalent. Aflatoxin M1, a hydroxylated metabolite, found primarily in animal tissues and fluids (milk and urine) as a metabolic product of aflatoxin B1 (Richard, 2007). Aflatoxins can affect a wide range of commodities including cereals, oilseeds, spices, and tree nuts as well as milk, meat, and dried fruit. Crops that are frequently affected by *Aspergillus* spp. include cereals (maize, sorghum, wheat, rice), oilseeds (soybean, peanut, sunflower, cotton seeds), spices (chili peppers, black pepper, coriander, turmeric, ginger) and tree nuts (Channaiah, 2011). It may contaminate many food products particularly under certain conditions: dry weather near crop maturity, high moisture during harvest, inadequate drying and storage of crops (PACA, 2012). The major sources of exposure are maize and groundnuts as these are the foods that are most susceptible to contamination and consumed in the greatest amounts (Ochieng et al., 2013).

Table 1
The most commonly associated mycotoxins with cereal grains following pre- and postharvest contamination.

Cereals	Pre-harvest	Postharvest
Barley	DON, NIV, ZEN, HT-2, T-2	OTA, Afla, Cit
Maize	DON, Fum, ZEN	ZEN, Afla,
Oats	DON, NIV, HT-2, T-2	OTA, Cit
Rice	–	Afla, Sterig, OTA
Rye	Ergot	OTA
Sorghum	Ergot	Afla
Wheat	DON, NIV, ZEN, Ergot	OTA, Afla, Cit

Note: Afla = aflatoxins; Cit = citrinin; DON = deoxynivalenol; Ergot = ergotamine; HT-2 = HT-2 toxin; T-2 = T-2 toxin, NIV = nivalenol; OTA = ochratoxin A; Sterig = sterigmatocystin; ZEN = zearalenone.
Adapted from Bryden (2012).

Aflatoxin contamination of key staples such as maize, groundnuts, and sorghum occurs above safe levels in many African countries. Prevalence data from Africa suggests that aflatoxin contamination in maize, groundnuts, and sorghum is higher than the European Union aflatoxin standard (4 ppb) and that of USA (20 ppb) in many countries (PACA, 2012). However, even aflatoxin exposure at low levels can result in measurable human health impacts. Exposure to aflatoxins occurs primarily through ingestion of contaminated foods and can cause hepatic and gastrointestinal injury and have immunosuppressive, teratogenic, and oncogenic effects (CDC, 2004). Aflatoxins may cause decreased production (milk, eggs, weight gains, etc.), are immunosuppressive, carcinogenic, teratogenic and mutagenic (Richard, 2007).

The WHO reported the burden of aflatoxin was high in the African Region, Western Pacific Region, and South-East Asia Region (WHO, 2015). The U.S. Centers for Disease Control and Prevention estimates that 4.5 billion people in the developing world may have chronic exposure to aflatoxins in the diet (CDC, 2013). More than 90% of people living in sub-Saharan Africa and portions of Asia are chronically exposed to aflatoxins at high levels (Turner, 2014).

Aflatoxin exposure has been linked to liver toxicity and cancer, and there is strong evidence it may also contribute to stunted growth in children (Schmidt, 2013), also confirmed linkage with synergistic effects with Hepatitis B, and potential association with immunosuppression. Chronic exposure to even low levels of contamination in crops consumed regularly increases liver cancer risk and can suppress the immune system. Ingestion of 2–6 mg/day of aflatoxin for a month can cause acute hepatitis and death (CDC, 2004). Liu and Wu (2010) revealed the global burden of aflatoxin may play a causative role in 4.6–28.2% of all global hepatocellular carcinoma (HCC) or liver cancer which is the third leading cause of cancer deaths worldwide. Aflatoxin burden was estimated using a counterfactual approach, estimating population attributable fractions from exposure assessment estimates and cancer potency factors, and applying these to WHO estimates for incidence and mortality by hepatocellular carcinoma (WHO, 2015).

The FDA has established action levels for aflatoxin content in food and feed products to protect human and animal health; 20 ppb

for maize, peanut products, cottonseed meal and other animal feeds and feed ingredients intended for dairy animals and when the intended use is not known (Channaiah, 2011).

2.2. Fumonisin

Fumonisins are carcinogenic mycotoxins produced by species of *Fusarium*, particularly *F. verticillioides* (*G. moniliformis*). Fumonisins are among the most important toxins regarding food and feed safety. Of the identified fumonisins produced by the fungus *F. verticillioides* (B1, B2, and B3), fumonisin B1 is the most prevalent toxin comprising approximately 75% of infections (Channaiah, 2011).

Maize is the major commodity affected by this group of toxins. *F. verticillioides* and *F. proliferatum* are among the most common fungi associated with maize, the most frequently contaminated food and can be recovered from both damaged and undamaged maize kernels (WHO, 2002). Fumonisins can also occur infrequently in other foods, such as sorghum, asparagus, rice, beer and mung beans (Richard et al., 2003; WHO, 2002). Hot climate, insect damage, and temperature stress may play a significant role for the cause. Increase in concentrations of fumonisins during storage does not appear to be a major problem, however, grains should be harvested without additional kernel damage, screened to remove broken kernels and stored dried and maintained at moisture concentrations <14% (Richard, 2007). As *F. verticillioides* and *F. proliferatum* grow over a wide range of temperatures but only at relatively high water activities (above about 0.9), fumonisins are formed in maize only before harvest or during the early stage of drying (WHO, 2002). Except under extreme conditions, fumonisin concentrations will not increase during grain storage.

In addition to their adverse effect on the brain, liver, and lungs in livestock animals, fumonisins can also affect the kidneys, pancreas, testes, thymus, gastrointestinal tract and blood cells (Channaiah, 2011). In all animal species studied, the liver was a target for fumonisin B1; the kidney was also a target in many species (WHO, 2002). The FDA has established guidance for fumonisin levels in human and animal feeds: 2 ppm for degermed dry milled maize products for humans; 4 ppm for whole or partially degermed dry milled maize products and cleaned maize intended for mass production; 5 ppm for equids and rabbits and no more than 20% of diet; 20 ppm for swine and catfish and no more than 50% of diet; 100 ppm for poultry being raised for slaughter and no more than 50% of diet; and 10 ppm for all other species or classes of livestock and pet animals and no more than 50% of diet (FAO, 2004).

2.3. Deoxynivalenol/vomitoxin

Deoxynivalenol (DON), also known as vomitoxin, is a trichothecene type that occurs predominantly in grains such as wheat, barley, oats, rye and maize, and less often in rice, sorghum, and triticale (Channaiah, 2011). DON may co-exist with ZEN, another mycotoxin produced by these organisms. They are produced by molds of the *Fusarium* genus, i.e. *F. culmorum* and *F. graminearum*, which are abundant in various cereal crops and processed grains. The organisms survive on residue left on the field from the previous season's crop, providing an inoculum source for the new crop (Richard, 2007).

DON is responsible for economic losses of billions of dollars worldwide each year, causing plant infection and contaminating grain, particularly wheat and barley. maize and small grains such as wheat, oats, and barley are the major crops affected but DON can be found in maize as well (Richard et al., 2003). In maize, the ear rot produced by *F. graminearum* may appear (Richard, 2007). In wheat *F. graminearum* infection is known as the head blight of wheat (Channaiah, 2011).

The FDA has established advisory levels for DON content in various commodities: 1 ppm on finished wheat products, e.g. flour, bran and germ that may potentially be consumed by humans; 10 ppm on grains and grain byproducts for cattle and chicken, not exceeding 50% of their diet; 5 ppm on grains and grain byproducts for swine, not exceeding 20% of their diet; and 5 ppm on grains and grain byproducts for all other animals not exceeding 40% of their diet (Channaiah, 2011; FAO, 2004).

2.4. Ochratoxins

Ochratoxins are mycotoxins produced mainly by species of *Aspergillus* and *Penicillium*, particularly *A. ochraceus* and *P. verrucosum*, with OTA as the most prevalent mycotoxin of this group (Channaiah, 2011; Richard et al., 2003). The infection of *Aspergillus* and *Penicillium* species occurs mainly during the post-harvest storage phase (Channaiah, 2011).

OTA occurs in a variety of foods. The highest reported occurrences of OTA contamination have been found in cereal grains, and to a lesser extent in grapes, wine, grape juice, and dried vine fruits (Clark & Snedeker, 2006). A significant feature of OT is that it occurs in a wide variety of commodities such as raisins, barley, soy products and coffee in varying amounts but at relatively low levels (Richard et al., 2003). The levels may accumulate in body tissues and fluids of either humans or animals consuming contaminated food because OT appears to be slowly eliminated from the body (Richard, 2007).

OT has been regarded as being produced in storage conditions which favor mold growth and toxin production, except for its occurrence in some crops such as grapes (Richard, 2007). The temperature and moisture requirements to grow and produce OTA are particularly relevant to grain storage. *P. verrucosum* grows only at temperatures below 30 °C and at a water activity above 0.80 (WHO, 2002). Little is known of the conditions necessary for involvement of the producing fungi in grains during development in the field. *A. ochraceus* grows at moderate temperatures and at a water activity above 0.8. It is found sporadically in a wide range of stored food commodities, including cereals, but is seldom the source of substantial concentrations of OTA (WHO, 2002). OTA is also known to occur in commodities like coffee and dried fruit.

OT is primarily a kidney toxin and it can damage the liver in high concentrations. OT affects animals mainly by disrupting the protein synthesis, affecting lipid peroxidation, causing DNA damage and oxidoreductive stress (Channaiah, 2011). OTA has been shown to be nephrotoxic in all mammalian species tested (WHO, 2002). OT tested as a carcinogen in rats and mice which will be suspect as the causative agent of human disease. This mycotoxin is nephrotoxic, immunosuppressive, teratogenic, and carcinogenic to animals and has been classified as a possible human carcinogen (Cicoňová, Laciaková, & Máté, 2010).

The European Union has established OT concentration in raw cereal grains should be 5 ppb, all products derived from cereals intended for direct human consumption 3 ppb, dried vine fruit (currants, raisins, and sultanas) 10 ppb (FAO, 2004).

2.5. Zearalenone

Zearalenone (ZEN), also known as F-2 toxin, is produced by some *Fusarium* species commonly by *F. roseum* and *F. moniliforme*. They are found in several cereal crops and their derived food products. ZEN is heat-stable and may co-occur with DON in grains such as maize, barley, oats, wheat, rice and sorghum (Channaiah, 2011; FAO, 2004; Richard et al., 2003). But most often this mycotoxin is found in maize. In wheat, sorghum and maize, ZEN occur in

pre-harvest grain but in other commodities, the surveys are insufficient to determine if ZEN occurred pre-or postharvest (Richard, 2007; WHO, 2002).

The fungus responsible for ZEN toxin production (*Fusarium* species) has also been shown to produce DON and T-2 under suitable weather conditions (Channaiah, 2011). ZEN can be formed at relatively cool temperatures and have led to increased levels of this mycotoxin during storage where conditions for fungal growth and mycotoxin formation were favorable (Richard, 2007). Alternating low and moderate temperatures during storage is favorable for ZEN production with an optimum at 28 °C.

The most notable effect of ZEN is that it causes the precocious development of mammae and other estrogenic effects in young gilts as well as a prepucial enlargement in young barrows. Studies in various species (rodents, rabbits, pigs, monkeys) including man have shown that ZEN has estrogenic and anabolic activity. Its major effects are on reproduction, including reproductive organs and their function, leading to hyperestrogenism (Kuiper-Goodman, Scott, & Watanabe, 1987). Swine are the most significantly affected species and are considerably more sensitive to ZEN than, for example, rodents and other species such as cattle and poultry (Richard, 2007; Richard et al., 2003). High concentrations of ZEN (50–100 ppm) in swine diets have been reported to adversely affect cycling, conception, ovulation, and implantation (Richard et al., 2003).

The overall weight of evidence suggests that an intake of less than 0.10 ppb per day would provide an adequate margin of safety to the consumer (Kuiper-Goodman et al., 1987). This should only be considered as a tentative tolerable daily intake, open to continual review. No adverse health effects are anticipated from ZEN exposure from maize cereals as compared to estimated tentative tolerable daily intake of Canadian exposure to ZEN. However, it is possible that exposure to ZEN from other food sources such as wheat, flour, or milk could increase the exposure estimates (Kuiper-Goodman et al., 1987).

3. Some common grains susceptible to mycotoxin

Grain is considered as the main mycotoxin vector in food or feeds. Fungi species become associated with the grain in the field, and can also grow during transport and storage if environmental conditions such as humidity and temperature are favorable. The concentration of mycotoxins in some common grains in different countries were tried to reviewed as follows.

3.1. Maize (Zea mays L.)

Fungi are the primary cause of spoilage in stored maize and can cause detrimental changes in appearance, quantity, and quality of stored grain, thereby reducing the end-use value of maize for food, feed, and biofuels (Channaiah & Maier, 2014). Maize can be contaminated with fumonisins, DON, ZEN, aflatoxins, and other mycotoxins, because of infection by toxigenic fungi, primarily in the genera *Fusarium* and *Aspergillus* (Munkvold, 2014). Aflatoxins and fumonisins are the major mycotoxins occurring in maize. OTA may occur in maize but is less common there than in the other commodities (Bullerman & Bianchini, 2014). The *fusarium* species (fumonisins, trichothecenes, and ZEN) is also capable of producing two or more toxins in maize. Table 2 displayed the most common mycotoxins affecting maize and their fungi species. *Fusarium* toxin recorded a 100% occurrence in the stored maize at a concentration range of 11–479 ppb in Nigeria (Adetunji et al., 2014). *Aspergillus* and *Fusarium* species can infect maize pre-harvest, and mycotoxin contamination can increase if storage conditions are poorly managed (Chulze, 2010). The *Penicillium* toxins in maize occur mainly during storage and when the harvest is delayed producing penicillic acid and OT (also *Aspergillus ochraceous*) (FAO, 2011).

The fungi can produce mycotoxins while maize is in the field, during processing, transportation, and storage (FAO, 2011). A wide spread of mycotoxins affecting maize in Africa due to worse postharvest handling. Spreading maize grain on the ground for drying prior to storage exposes the maize grain to mold spores under conditions of high relatively humidity and temperature, accelerating development of the pathogen.

In recent years, reports have associated aflatoxins with diminished human health and export opportunities in many African nations (Probst, Bandyopadhyay, & Cotty, 2014). The FDA has set advisory or guidance for aflatoxin at 20 ppb and for fumonisins at 2–4 ppm levels in maize and maize products (Channaiah, 2011; FAO, 2004; Richard et al., 2003). In most of the African countries, the level is above the limit which is a risk for human health. For example, aflatoxin tests were carried out on 245 maize samples in west Africa (Benin, Burkina Faso, and Ghana), with 53% having levels above 20 ppm in both PICS and woven bags (Baoua, Amadou, Ousmane, Baributsa, & Murdock, 2014). In a study in Kenya, of about 350 samples of processed maize products collected in seven markets, 55% had levels of aflatoxin of >20 ppb, 35% had >100 ppb and 7% had >1000 ppb (Lewis et al., 2005). In Nigeria aflatoxin B1 and fumonisin B1 in maize had shown were exceeding the maximum acceptable limit set by European Union Commission while DON was below the limit (Adetunji et al., 2014).

Another study in Sub-Saharan Africa (Burkina Faso, Cameroon, DR Congo, Ethiopia, Ghana, Ivory Coast, Kenya, Malawi, Mali, Mozambique, Rwanda, Senegal, Sierra Leone, Somali, Tanzania, Uganda, Zambia and Zimbabwe) showed that sampled maize frequently tested positive for aflatoxins (65%), fumonisins (81%), and DON (40%) indicating the presence of fungi capable of producing the respective toxins (Probst et al., 2014). The result revealed that percentage of samples exceeding US limits for total aflatoxins (regulatory limit), fumonisins (advisory limit), and DON (advisory limit) were 47%, 49%, 4%, respectively.

3.2. Wheat (Triticum aestivum L.)

The major mycotoxins occurring in wheat and wheat products are OTA, DON, ZEN, T-2 and HT-2 were analyzed (Gilbert & Pascale, 2014). Ochratoxin, produced primarily by *Penicillium verrucosum*, and DON and ZEN, produced primarily by *Fusarium graminearum* are the primary mycotoxin contaminants of wheat (Marasas, Gelderblom, Shephard, & Vismer, 2008; Moretti, Waalwijk, & Geisen, 2014). OTA is the most common, the most studied, and the most toxic of the OT and may be found in wheat grain, all milled wheat fractions, and bread and pasta products (Jacobsen, 2014).

Mycotoxin contamination of wheat results from fungal pathogens may during flowering, delayed harvest due to wet conditions, and in storage. Several species of *Fusarium*, *Penicillium*, and *Alternaria* may infect grain if the harvest is delayed due to wet conditions, and isolates of *Aspergillus* and *Penicillium* may infect during storage if there is sufficient moisture to support fungal growth (Jacobsen, 2014). Aflatoxin and sterigmatocystin are found only postharvest under improper storage conditions, while the others may occur in the production field, when the harvest is delayed or when the grain is stored improperly (Jacobsen, 2010). They can only contaminate wheat when improperly stored and cannot result at pre-harvest as in the case of other grain. Also, other mycotoxins like penicillic acid and citrinin often are found in improperly stored wheat. Wheat is not a high-risk crop for aflatoxin contamination, although aflatoxin, primarily aflatoxin B1, contamination does occur in wheat grain, flour, and pasta (Jacobsen, 2014). In Poland, the maximum acceptable DON level (1250 ppb) was exceeded in 10

Table 2
Mycotoxins of greatest concern in maize and the fungi that produce them.

Mycotoxin	Fungal species
Aflatoxins	*Aspergillus flavus*, *A. parasiticus*, *A. nomius*
Ochratoxin	*Aspergillus ochraceus*, *A. niger*, *Penicillium verrucosum*
Fumonisins	*Fusarium verticillioides*, *F. proliferatum*, *F. subglutinans*
Moniliformin	*Fusarium proliferatum*, *F. subglutinans*, *F. thapsinum*
Deoxynivalenol (DON, vomitoxin)	*Fusarium graminearum*, *F. culmorum*, *F. crookwellense*
Zearalenone	*Fusarium graminearum*, *F. culmorum*, *F. crookwellense*
T-2 toxin	*Fusarium poae*, *F. sporotrichioides*, *F. langsethiae*

Adopted from Bullerman & Bianchini, (2014).

samples (out of 147 total) of cereals including wheat, while the maximum acceptable OTA level (5 ppb) was exceeded in a single sample (Bryła et al., 2016).

3.3. Sorghum (Sorghum bicolor L.)

Sorghum is subject to contamination by a range of fungi both in the field and after harvest (Chala et al., 2014). The most commonly reported mycotoxins in sorghum are aflatoxins, fumonisins, and ZEN, with others such as OTA, cyclopiazonic acid, gliotoxin, and trichothecenes reported much less often (Leslie, 2014).

The concentration of aflatoxin (0–26 ppb), OTA (54.1–2106 ppb), DON (40–2340 ppb), FUM (2117 ppb) and ZEA (32 ppb) in cereals including sorghum were reported from Ethiopia (Ayalew, Fehrmann, Lepschy, Beck, & Abate, 2006; Darwish, Ikenaka, Nakayama, & Ishizuka, 2014). Another study in Ethiopia revealed that ZEN was the most common major mycotoxin occurring in sorghum up to 374.3 ppb with an average of 43.8 ppb while fumonisin B1 was the second most dominant major mycotoxin with an average level of 15 ppb (Chala et al., 2014). The average aflatoxins B1 and G1 concentrations in sorghum have been higher than European Commission standards. The study in Kenya had shown that *Aspergillus* species was predominant in sorghum from farmers' stores, while *Fusarium* species was predominant in freshly harvested sorghum grains (Kange, Cheruiyot, Ogendo, & Arama, 2015). In Burkina Faso aflatoxin B1 and OTA were not found in all the sorghum beer samples; however, the sorghum malt samples contained aflatoxin B1 with an average of 97.6 ± 88.2 ppb (Bationo et al., 2015).

In sorghum-based products aflatoxin from 6.4 to 62.2 and nivalenol from 418 to 667 were observed in four countries of the Mediterranean region (Spain, Italy, Morocco and Tunisia) (Serrano, Font, Ruiz, & Ferrer, 2012). Ediage, Van Poucke, and De Saeger (2015) analyzed 10 red sorghum samples sourced from markets in Belgium and Germany. A total of 90% (9/10) of the sorghum samples were tested positive for one or more mycotoxins. The samples were positive for the following mycotoxins; aflatoxin B1 (50 ppb), alternariol monomethyl ether (<LOQ – 79 ppb), fumonisin B1 (<LOQ – 95 ppb), fumonisin B2 (<LOQ), fumonisin B3 (<LOQ), T2 (<LOQ) and ZEN (<LOQ); however, maximum limits were not exceeded except for one of the 10 samples (10%) contaminated with aflatoxin B1 at 50 ppb.

3.4. Millet (Eleusine coracana L.)

In Ethiopia, ZEN was the most common major mycotoxin occurring in finger millet up to 458.7 ppb with an average of 76.5 ppb while fumonisin B1 was the second most dominant major mycotoxin with an average level of 16 ppb (Chala et al., 2014). The mean total aflatoxin level of millet flour and porridge were 14.0 ± 1.22 in southwestern Uganda (Kitya, Bbosa, & Mulogo, 2010). A preliminary survey in Côte d'Ivoire revealed that about 17–204 ppb OTA in millet were observed (Sangare-Tigori et al., 2006). Jurjevic, Wilson, Wilson, and Casper (2007) determined changes in fungi and mycotoxins in pearl millet under controlled storage conditions in Southeastern USA. In this study aflatoxin contamination, up to 798 ppb with an average of 174 ppb were observed at high-moisture grain stored at 25 °C. The maximum concentration of mycotoxins like moniliformin (92.1 ppb) and beauvericin (414.6 ppb) were analyzed from pearl millet in USA (Wilson et al., 2006). Aflatoxin and fumonisin up to 7.1 and 121 ppb were also obtained in this study, respectively.

3.5. Rice (Oryza sativa L.)

Mycotoxin contamination is less commonly reported for rice than for many other cereals, however, some reports that rice has been contaminated with mycotoxins (Tanaka, Sago, Zheng, Nakagawa, & Kushiro, 2007). The natural occurrence of mycotoxins like aflatoxin B1, aflatoxin B2, DON, OTA, and ZEN was observed in newly harvested rice grains (Dors, de Almeida Pinto, & Badiale-Furlong, 2009). The most important mycotoxins identified and often occur in rice include aflatoxins, citrinin, DON, sterigmatocystin, fumonisins, ZEN, cyclopiazonic acid, patulin, gliotoxin and some trichothecenes which are produced by *Aspergillus*, *Penicillium*, and *Fusarium* genera (Ferre, 2016; Koesukwiwat, Sanguankaew, & Leepipatpiboon, 2014; Tanaka et al., 2007). Aflatoxin B1 and OTA were widely studied in many countries may be due to their adverse health effect on health. The natural occurrence of citrinin in rice has only been identified in a small number of studies (Ferre, 2016). Ferre (2016) also, described that very little fumonisins are known about the incidence and favorable conditions of toxins appeared in rice.

The European Commission Regulation has set the maximum limits of aflatoxin B1 at 2 ppb in rice, 0.1 ppb for cereal-based baby foods, 4 ppb for others aflatoxins; where also the commission established OTA at 5 ppb in rice, 3 μg/kg of OTA in rice products and at 0.5 ppb in food made for babies and children (EC, 2006). In some countries, the level is above the limit.

In Nigeria aflatoxins B1, OTA and ZEN are among the most significant and abundant mycotoxins found in rice in the range of 20–1642 ppb, 24–1164 ppb, 24–1169 ppb, respectively (Makun, Gbodi, Akanya, Salako, & Ogbadu, 2007). In the same country aflatoxins from 28 to 372 ppb and OTA 134–341 ppb were found in rice while the occurrence of ZEN, DON, fumonisin B1 also found relatively at low levels (Makun, Dutton, Njobeh, Mwanza, & Kabiru, 2011).

The levels of total aflatoxins, aflatoxin B1 and OTA in rice were higher than the maximum tolerable limits set for cereals and cereal products (4, 2 and 3 ppb, per the EC Regulation) in Turkey (Aydin, Aksu, & Gunsen, 2011). In Malaysia citrinin (0.23–20.65 ppm), aflatoxin (0.61–77.33 ppb) and OTA (0.23–2.48 ppb) were quantified in red rice; citrinin and aflatoxin levels exceeded EU and the country's limits (Samsudin & Abdullah, 2013). Park, Choi, Hwang,

and Kim (2005) were analyzed fumonisins, OTA, trichothecenes, and ZEN in Korean polished rice. OT A (1.8–7.3 ppb) was the most commonly detected mycotoxin analyzed in this study; moreover, its level in some samples was above the EU tolerable limit (3 ppb). Aflatoxin concentrations ranging from 0.2 to 1.8 ppb were registered in a trial study conducted with different kinds of rice from different supermarkets in the United Kingdom and Germany (Ferre, 2016).

3.6. Groundnut (*Arachis hypogaea L.*)

About 39.9 million metric tons of groundnut produced per year but the production is faced a major problem worldwide due to mycotoxin contamination (Torres, Barros, Palacios, Chulze, & Battilani, 2014). The most significant mycotoxins found in groundnut include aflatoxins, OT, patulin, fumonisins, ZEN and some trichothecenes including DON (Abia et al., 2013; Ezekiel, Sulyok, Warth, Odebode, & Krska, 2012). Aflatoxins are the most significant problem regarding the quality of groundnut worldwide (D'Mello, 2003), causing high risk and contaminating the grain frequently. Especially in Africa where the regulation is less the prevalence is at high risk. Most of the research in Africa countries revealed that the levels of aflatoxin in groundnut exceeds maximum tolerable limits of the European Commission Regulations and FAO/WHO.

In the Democratic Republic of Congo, out of 60 samples, 70% of the peanut samples were exceeded the maximum limit of 5 ppb prescribed by the World Health Organization (Kamika & Takoy, 2011). The study in Malawi also showed that aflatoxin B1 contamination level in some of the groundnut samples was greater than the limit set by European Commission standard and US limit which is 4 ppb and 20 ppb, respectively (Monyo et al., 2012; Waliyar et al., 2015). The overall aflatoxin B1 levels in groundnut kernels and paste increased during storage at the market level in the three districts of Mali were above permissible levels (>20 ppb) (Waliyar et al., 2014). Natural occurrence of mycotoxins in peanut cake from Nigeria showed that in about 90% samples aflatoxins exceeded the USDA maximum limit of 20 ppb (Ezekiel et al., 2012).

From 120 samples of groundnut, about 93 (77.5%) contain aflatoxin varying the levels in between 15 ppb and 11,900 ppb in Eastern Ethiopia (Chala, Mohammedb, Ayalewc, & Skinnes, 2013). The results clearly revealed heavy aflatoxin contamination of groundnut samples in Ethiopia is far beyond the Food and Agricultural Organization of the United Nations/World Health Organization (FAO/WHO) standard. All (168) samples of groundnut kernels from Northern Ethiopia were also found 100% positive for *Aspergillus* species (*A. flavus* and *A. niger*); varying among locations contain aflatoxin concentrations ranging from 0.1 to 397.8 ppb (Assefa, Teare, & Skinnes, 2012).

4. Factors affecting the occurrence of mycotoxin in grains

The factors affecting mycotoxin contamination of grain include biological factors (susceptible crop), environmental factors (temperature, moisture availability, humidity, mechanical injury, and insect/bird damage), harvesting (crop maturity, temperature, moisture, and handling), storage (structure, conditions, moisture, and temperature), handling and processing. Important factors which are affecting mycotoxin production in food chains are shown in Fig. 2.

The growth of fungi in storage is governed by the composition of nutrients in the grain, moisture and temperature conditions and biotic factors like competition or the presence of stored product insects (Atanda et al., 2011). The temperature and moisture content of the grain or commodity are the most critical factors favoring fungal growth and mycotoxin production. Relative humidity is another factor influencing the moisture content of stored grain resulting in water available for mold growth and subsequent mycotoxin production. In general, molds grow at a temperature range of 10 °C–40.5 °C, above 70% relative humidity and a pH range of 4–8 (Channaiah, 2011). The optimum temperature and water activity for mycotoxin production in grains are shown in Table 3.

Insect infestation of grain is another factor that promotes fungal inoculation and subsequent mycotoxin contamination in several ways (Abbas et al., 2013; Jouany, Yiannikouris, & Bertin, 2009; Wagacha & Muthomi, 2008). Avantaggio, Quaranta, Desidero, and Visconti (2002) reported the fungal infection through physical damage of insect feed on maize ears in the field and storage. Insects burrowing through the husks or down the silk channel can open infection routes for air or dust-borne fungal pathogens. Insect herbivory creates kernel wounds that give fungi access to the endosperm, and insects themselves serve as vectors of fungal spores (Jouany et al., 2009). Insects carry the spores from plant surfaces to the interior of the stalk or kernels or create infection wounds due to the feeding of the larvae on stalks or kernels. Wounding by insects may provide infection courts and allow kernels to dry down to moisture content more favorable for the growth of *A. flavus* and aflatoxin production (Wagacha & Muthomi, 2008). During storage, insects, due to their metabolic heat and water, can increase the water activity and temperature of grain to levels suitable for fungal growth. Insects can produce metabolic heat which generates water via condensation on surfaces due to temperature differentials and develops classic hot spots which can quickly result in heating and complete spoilage (Magan, Hope, Cairns, & Aldred, 2003). Control of storage insects through the sorting out of damaged grain, the use of appropriate storage insecticides and "awareness" of the farmers of the risk that insects and aflatoxins present to their stored grain will reduce the risks.

Mechanical damage to kernels makes them much more vulnerable to invasion by storage molds, including *A. flavus*. Under any given environmental conditions fungal growth is several times faster in damaged compared to intact kernels. Mechanical damage is conducive to the entry of spoilage fungi in insufficiently dried grain (Magan et al., 2003).

5. Postharvest mitigation of mycotoxins

In fact, mycotoxins are huge detrimental effect on human and animal health, economic loss, and food security problem. An integrated system management approach is important to mitigate the problem. Comprehensive research is important to understand crop biology, agronomy, fungal ecology, harvesting methods, storage conditions and detoxification methods of mycotoxin (Bryden, 2009). Several mitigation strategies have been developed to prevent the growth of fungi as well as to decontaminate and detoxify food, which contaminated by mycotoxin (Kabak, Dobson, Var, & l, 2006). There is pre- and postharvest mitigation strategies are available to reduce the contamination of mycotoxins in grains (Fig. 3). Pre-harvest methods include; using resistant varieties, field management, use of biological and chemical agents, harvest management (Adegoke & Letuma, 2013, pp. 123–136).

Postharvest interventions that reduce mycotoxin include rapid and proper drying, proper transportation and packaging, sorting, cleaning, drying, smoking, postharvest insect control, and the use of botanicals or synthetic pesticides as storage protectants (Hell & Mutegi, 2011; Wild et al., 2015, p. 9). Postharvest interventions to reduce mycotoxin exposure should include education programmes and awareness campaigns that will facilitate best practices (Wild et al., 2015, p. 9). Good storage conditions, use of natural and chemical agents and irradiation are reported to prevent mycotoxins

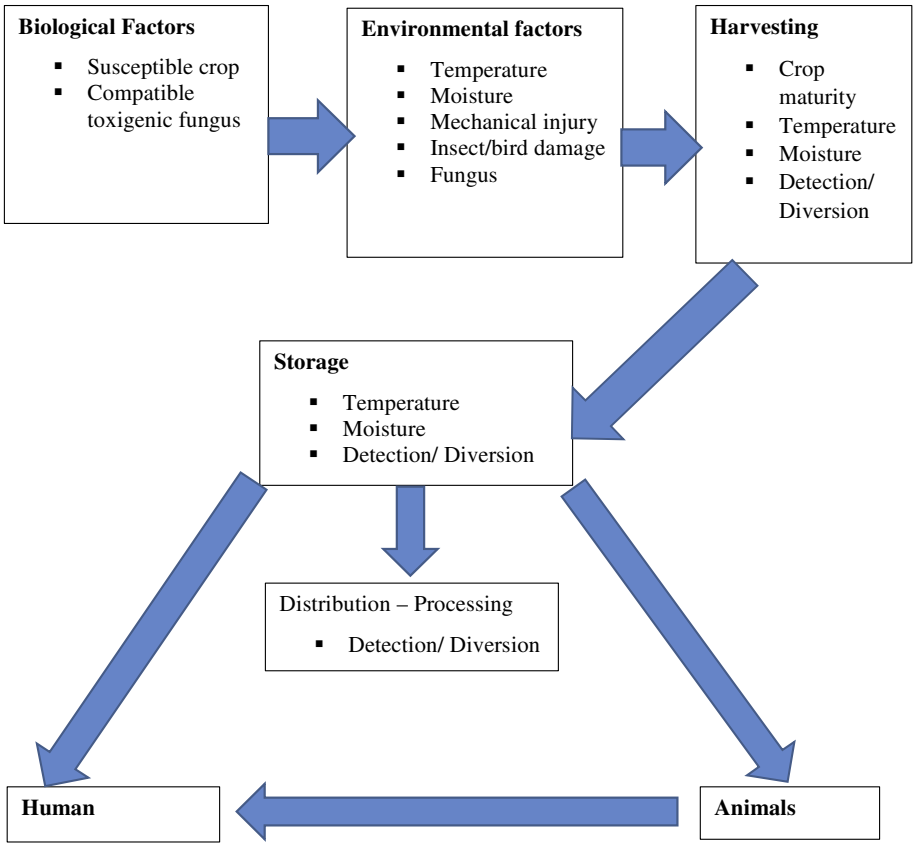

Fig. 2. Factors affecting mycotoxin occurrence in the human food and animal feed chains.
Adapted from Bryden (2012) and Pestka & Casale (1990).

Table 3
Optimum temperatures and water activity for mycotoxin production.

Mycotoxin	Temperature (°C)	Water activity
Aflatoxin	33	0.99
Ochratoxin	25–30	0.98
Fumonisin	15–30	0.9–0.995
Zearalenone	25	0.96
Deoxynivalenol	26–30	0.995
Citrinin	20–30	0.75–0.85

Adapted from Milani (2013).

after harvest (Adegoke & Letuma, 2013, pp. 123–136; Kabak et al., 2006). Effective postharvest management of stored commodities requires clear monitoring criteria and effective implementation in relation to abiotic and biotic factors, hygiene and monitoring to ensure that mycotoxin contamination is minimized and that stored grain can proceed through the food chain for processing (Magan & Aldred, 2007).

A control program for mycotoxins from field to table should involve the criteria of an HACCP approach which will require an understanding of the important aspects of the interactions of the toxigenic fungi with crop plants, the on-farm production and harvest methods for crops, and to the development of processed foods for human consumption as well as understanding the marketing and trade channels including storage and delivery of foods to the consumer's table (Richard, 2007). The inclusion of mycotoxin control in HACCP plans, an important aspect of an overall management approach, should include strategies for prevention, control, and quality from farm-to-fork (Murphy, Hendrich, Landgren, & Bryant, 2006). The effective use of HACCP-based postharvest approach to nearly eliminate aflatoxins from peanuts was displayed in Table 4.

5.1. Harvesting

Postharvest strategies for preventing mycotoxin contamination in stored grains begin at harvest. The timing of harvest greatly affects the extent of mycotoxin contamination. Excessive numbers of over mature or very immature peanut pods at harvest can be reflected in high levels of aflatoxin in the final product (Torres et al., 2014). Delayed harvest significantly increased the level aflatoxin in maize (Kaaya, Warren, Kyamanywa, & Kyamuhangire, 2005), result in poor quality seed due to mold infections and subsequent aflatoxin contamination of the seeds/pods. Greater ear rot infection and higher levels of aflatoxins, DON, nivalenol, or fumonisins may be associated with delayed harvest for grain maize (Munkvold, White, & Johnson, 2003). Mycotoxin content increases with delayed harvest coupled with rain (Channaiah, 2011).

Agricultural producers need to avoid factors that cause crop stress during harvesting such as early harvesting and collecting damaged kernel during at harvest. Freshly harvested cereals should be cleaned to remove damaged kernels and other foreign matter. If 10% or more of the ears have 10–20% mold damage or are lodged, the field should be scheduled for the earliest possible harvest (Munkvold, 2014). Avoiding mechanical damage and grain contact with soil at harvesting stage also minimize contamination of fungal infection. Delage, d'Harlingue, Ceccaldi, and Bompeix (2003) revealed that crops which have been physically damaged being more susceptible to fungal growth. Proper cleaning of harvested

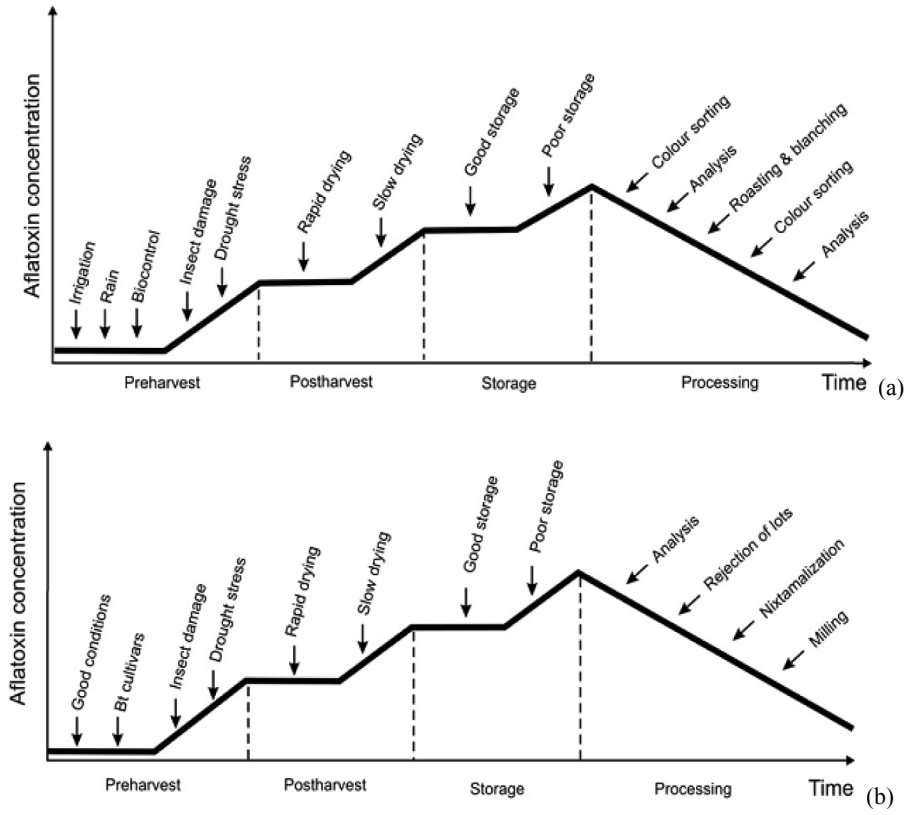

Fig. 3. Aflatoxin formation and reduction in (a) peanuts and (b) maize.
Adapted from Pitt et al. (2013).

Table 4
HACCP based reduction of aflatoxins postharvest.

Technology	Aflatoxin level (ppb)	% Reduction
Farmers stock	217	–
Belt separator	140	35
Shelling plant	100	29
Color sorting	30	70
Gravity table	25	16
Blanching/color sorting	2.2	91
Re-color sorting[a]	1.6	27

Results were obtained from processing of a 400 kg lot of contaminated peanuts.
[a] Data based on medium category peanuts only.
Adapted from Murphy et al. (2006).

grain is a must to reduce mycotoxin concentration. Containers (e.g., wagons, trucks) to be used for collecting and transporting the harvested grain from the field to drying facilities, and to storage facilities, should be clean, dry and free of insects and visible fungal growth before use and re-use (CAC, 2012).

5.2. Drying

After harvesting, safe level drying condition of grains to the recommended moisture level are crucial for mitigation of mycotoxins. Drying should be done soon after harvest. Slow drying can increase the concentration of aflatoxin and other mycotoxins (Fig. 3). Grain dried below 14% moisture content can arrest further mold growth and mycotoxin production (Channaiah, 2011). A common recommendation is that harvested field crops should be dried as quickly as possible to safe moisture levels of 10–13% for cereals and 7–8% for oilseeds (Hell et al., 2008). Magan and Aldred (2007) further recommended that efficient and prompt drying of cereal grains for safe moisture levels (maize, 14%; rice, 13–14%; barley, 14–14.5% and canola or rapeseed, 7–8%) will prevent entering of OTA and other mycotoxins after harvesting. To stop fungal growth and avoid mycotoxin accumulation, grain should be dried to less than 0.7 a_w, i.e., usually to no more than 14% and preferably below 13% (Channaiah & Maier, 2014). In Guinea, 60% reduction in the mean aflatoxin levels were reported with proper drying and storage of groundnuts (Turner et al., 2005).

Poor drying can result in *P. verrucosum* colonization occurring, and the potential for pockets of mycotoxin contaminated grain to be present in silos (Magan & Aldred, 2007). Slow drying of grains reported increasing the concentration of mycotoxin whereas rapid drying is important to maintain the concentration at a low level (Pitt, Taniwaki, & Cole, 2013). For example, sun drying of some commodities in high humidity may result in fungal during storage infection (CAC, 2012). A suggested replacement for sun drying is the use of solar dryers, because they dry crops faster and more efficiently and provide a controlled environment that offers improved sanitation (Wild et al., 2015, p. 9).

5.3. Storage

Grains are subjected to quality loss during storage. In developing countries, inadequate storage practices account for 20–50% of crop losses (Wild et al., 2015, p. 9). The quality loss in stored grains is caused mainly by deterioration, a natural process which breaks down organic matter through either physical/chemical processes or biological processes which contained nutrients and energy are used by other life forms (Mills, 1996). Store fungi include all species of *Aspergillus*, *Fusarium,* and *Penicillium* (Atanda et al., 2011). Cereal

grains are particularly susceptible to grow by *Aspergilli* in storage environments (Kabak et al., 2006), where the main toxigenic species are *A. flavus* and *A. parasiticus* for aflatoxins (Sweeney & Dobson, 1998), and *Penicillium verrucosum* is the main producer in cereals for OTA (Lund & Frisvad, 2003).

During storage control of the moisture, temperature and relative humidity of the grains are the main mitigation strategies to minimize the growth of fungi, and ultimately grain quality deterioration. Moisture control is the main critical one for prevention of mycotoxins in grains. The following moisture contents are considered safe during storage: 14%–14.5% for wheat, barley, and oats; 14% for maize; 13%–14% for rice and 7%–8% for rapeseed (Channaiah, 2011). During storage, once the grain a_w drops below 0.9, *fusarium* species like fumonisins, DON and NIV production cease and will not rise. Even if very high moisture occurs due to water ingress, competition with other microorganisms at such high-water activities will prevent any significant increase in fumonisin levels (Pitt et al., 2013). Sweeney and Dobson (1998) found aflatoxins can be produced at a_w values ranging from 0.95 to 0.99 with a minimum a_w value of 0.82 for *A. flavus*, while the minimum a_w for OTA production is 0.80. Generally, provided grain is stored at a moisture content equivalent to $\leq$0.70 a_w then no spoilage will occur (Magan et al., 2003).

Cereal grains require above 70% of relative humidity for storage molds (Mills, 1996). It has been reported that *A. flavus* will not invade grain and oilseeds when their moisture contents are in equilibrium with a relative humidity of 70% or less (Kabak et al., 2006). In peanut *A. flavus* or *A. parasiticus* cannot grow or produce aflatoxins at water activities less than 0.7, where relative humidity should be kept below 70% (CAC, 2004, p. 55). As *A. flavus* and *A. parasiticus* are xerophiles, aflatoxin production in peanut will continue to occur if storage floors are damp, or humidity rises significantly above 80% RH (Pitt et al., 2013).

Another most important parameters used to prevent the growth of molds in the stored grain is control of temperature. Ideally, grain should be cooled after drying and maintained at 1 °C–4 °C for the duration of storage, while during the summer months the grain temperature can be maintained between 10 °C and 15 °C (Munkvold, 2003). At low or cold temperature, fungal contaminants not killed, but their growth and metabolism are minimal. Aflatoxins are produced at temperatures ranging from 12 to 40 °C (Sweeney & Dobson, 1998), while OTA production by *P. verrucosum* occurs between 10 and 25 °C (Olsen et al., 2003). *A. flavus* has an unusually high tolerance to heat, compared with other fungi; it thrives in temperatures approaching 37.8 °C and even higher (Schmidt, 2013). Temperatures between 0 and 10 °C are optimal for minimizing deterioration and fungal growth in peanut during long time storage (CAC, 2004, p. 55). If peanuts are dried effectively and kept dry in well-designed silos where moisture migration does not occur, or are stored under refrigeration below 10 °C, aflatoxin concentrations do not increase (Pitt et al., 2013).

It revealed that a temperature rise of 2–3 °C may indicate mold growth or insect infestation (CAC, 2012). Temperature control is achieved by aerating the grain when outside air temperature is within the desired range and humidity is low (Munkvold, 2003). Aeration is essential for control of mycotoxin production in grain storage, by controlling temperature and evaporating moisture that has migrated and condensed in the bin. It is key to maintaining low, uniform grain temperatures and avoiding the localized hotspots that can result from the growth of storage fungi (Channaiah & Maier, 2014).

Selection of types and structure of grain storage are also important to mitigate mycotoxins. Storage in well-constructed silos will prevent moisture migration and limit aflatoxins and other mycotoxins production. However, storage in less developed economies is often less satisfactory, in uninsulated metal silos subject to moisture migration, buildings with leaky roofs, or earthen floors, or in outdoor wooden bins (Pitt et al., 2013). PICS bags are also reported less aflatoxin contamination as compared to woven or cloth bags (Baoua et al., 2014; Sudini et al., 2015). PICS bags arrest the development of storage insect pests, which can spread the mold through the container.

Codex Alimentarius Commission (CAC, 2012) recommended how to prevent and reduce mycotoxin during storage; storage facilities should be dry, well-vented structures that provide protection from rain, drainage of groundwater, protection from entry of rodents and birds, and minimum temperature fluctuations, aerate the grain by circulation of air through the storage area to maintain proper and uniform temperature levels throughout the storage area. Also, the use of good housekeeping procedures and approved preservative (e.g., organic acids such as propionic acid) minimize the levels of insects and fungi in storage facilities. Sanitation, loading, aeration and monitoring (SLAM) are critically important best management practices for stored grains (Channaiah & Maier, 2014). Observations including inspection for overall temperature, crusts or mold on the grain, moisture in the bin, moldy odor, and warm spots are also important (Munkvold, 2003).

5.4. Modified atmosphere storage

Both reductions in oxygen tension and increase in carbon dioxide concentrations can have profound effects on the growth of fungi (Atanda et al., 2011). Low oxygen concentrations (<1%) and/or increased concentrations of CO_2 or N_2 have been found to be highly effective in preventing the development of mold on grain and in inhibiting selected mycotoxins, e.g. aflatoxins, OT, patulin, penicillic acid and T-2 (Paster & Bullerman, 1988). Hermetic or sealed storage system offered by triple layer bags presumably induced direct respiration effects on the molds via low O_2 and high CO_2 that reduced the aflatoxin accumulation in seeds (Sudini et al., 2015). Modifying the gasses in atmospheres where grains are stored can be used in the prevention of mycotoxin production. Decreasing O_2 to <0.14% and increasing CO_2 to >50% is required for inhibition of mycelial growth and will prevent mycotoxin (Magan & Aldred, 2007). However, the levels of CO_2 needed to inhibit mold growth are much higher than those required for the inhibition of mycotoxin production (Paster & Bullerman, 1988). Atmospheres greater than 30% (for example, 30–60% CO_2) can be used for preventing OTA production during storage or transportation of grains (Adegoke & Letuma, 2013, pp. 123–136). Elevated CO_2 of >75% are required to ensure that growth of mycotoxigenic molds does not occur in partially dried grain (Magan & Aldred, 2007). The degree of inhibition achieved by elevated CO_2 concentrations is dependent on other environmental factors, such as relative humidity (RH) and temperature (Paster & Bullerman, 1988). Nevertheless, the biosynthetic pathways for mycotoxin production are merely blocked, but not damaged by high CO_2 levels.

5.5. Processing

Various types of processing like physical or mechanical, chemical, or thermal methods are applied to food that may affect mycotoxins contamination (Bullerman & Bianchini, 2014; Kabak, 2009; Kaushik, 2015; Milani & Maleki, 2014). The processes like roasting and extrusion that utilize the higher temperatures (above 150 °C) have greater effects on mycotoxin dissipation (Kaushik, 2015). Processing techniques may reduce mycotoxin concentration, but cannot destroy totally and can contaminate finished processed foods and feeds (Bullerman & Bianchini, 2014; Kaushik, 2015; Milani & Maleki, 2014).

Physical processes carried out before milling (such as sorting, cleaning, de-branning) are interesting and efficient methods to reduce the grain mycotoxin content before milling. Cleaning maize to remove damaged or moldy kernels reduces fumonisins in foods while milling increases their concentration in some and reduces their concentration in other products (Humpf & Voss, 2004). In developed countries, sorting and grain cleaning techniques are required to reduce mycotoxin contamination, notably in grains contaminated by ergot and in nuts (Wild et al., 2015, p. 9). Tibola, Fernandes, and Guarienti (2016) reported cleaning and sorting significantly reduced mycotoxins in wheat and its by-products. They found that cleaning method contributed to DON reduction more than 3000 ppb with a mean of approximately 500 ppb in milled wheat samples. The effect of physical and mechanical processes and reported of mycotoxins concentration in cleaned wheat can vary from 7 to 63% for DON, from 7 to 100% for NIV and from 7 to 40% for ZEN, when compared with uncleaned wheat (Cheli, Pinotti, Rossi, & Dell'Orto, 2013). Savi et al. (2016) found bran fraction had the highest mean concentration of DON (2278 ppb), followed by milled wheat and finished flour (1895 ppb and 1305 ppb). This study revealed that distribution factor in the finished flour (69%) fraction demonstrates that DON was reduced when compared to milled wheat, by the contrast of bran fraction that presents higher DON levels (120%). Cleaning of raw grain in industrial cleaners reduced DON content by 38.2% and NIV by 34.8%, while cleaning in the traditional grain cleaner device reduced DON content by 20.8% and NIV content by 15.5% (Lešnik, Cencič, Vajs, & Simončič, 2008).

Removal of damaged grain by density segregation can reduce DON and ZEN concentration in maize and wheat (Jackson & Bullerman, 1999). Sydenham, van der Westhuizen, Stockenström, Shephard, and Thiel (1994) reported cleaning by using sieving out, fines' (<3 mm) from intact maize kernels (0.53–1.89 ppb of total fumonisins) reduced fumonisin levels (FB_{1-3}) by 26–69%. Sorting of discolored grain kernels by hand, or preferably by machine, can also remove a very high proportion of aflatoxins.

In the UK, a total of 90–95% of all *Fusarium* mycotoxin contamination in the raw oats is removed during the production of oat flakes (Scudamore, Baillie, Patel, & Edwards, 2007). Milani and Maleki (2014) also, reviewed OT and fumonisin was reduced by processing of breakfast cereals such as in the maize flake process. Nixtamalization removes almost all fumonisins as well as aflatoxins, resulting in tortillas and other maize-based foods being substantially free of these mycotoxins (De La Campa, Miller, & Hendricks, 2004). Since fumonisins are water-soluble and nixtamalization (cooking in alkaline water) lowers the fumonisin content of food products if the cooking liquid is discarded (Humpf & Voss, 2004).

Baking is another food processing method reported to reduce mycotoxin concentration. Kaushik (2015) reviewed baking reduced 13% aflatoxin in maize muffin, 24–71% DON in bread and cookies, 16–28% fumonisin in maize muffin, 75% OT in a biscuit. Since baking involves high temperature which causes the destruction of mycotoxins. The average reduction in DON concentration after baking (70 min at 195–235 °C) was 47.2% for bread baked in the industrial oven and 48.7% for bread baked in the log fire oven (Lešnik et al., 2008). Baking maize muffins spiked with 5 ppb FB1 at 175 and 200 °C resulted in 16% and 28% reductions in toxin levels, respectively, whereas the frying of tortilla chips at 190 °C for 15 min caused a 67% reduction in fumonisin levels (Jackson, Katta, Fingerhut, DeVries, & Bullerman, 1997). Castelo, Sumner, and Bullerman (1998) found baking maize muffin mix (spiked with 5 ppb FB1) lead to no significant loss of FB1 at 204 °C; 48% loss of FB1 at 232 °C. The effect of baking on non-yeast products was observed ranging from no effect to 35% reduction of DON (Young, Fulcher, Hayhoe, Scott, & Dexter, 1984). Abbas, Mirocha, Pawlosky, and Pusch (1985) reported that DON was not destroyed in the bread baked from the naturally contaminated whole wheat flour. Baking at 210 °C for 14 min had no significant effect on DON levels (Lancova et al., 2008). DON is stable at 120 °C, moderately stable at 180 °C and partially stable at 210 °C (WHO, 2001). During the making of bread from wheat flour, up to 100% of ergot alkaloids are destroyed, whereas vomitoxin is stable (Scott, 1984).

Roasting is considered one of the most effective methods of reducing mycotoxin levels in certain commodities. Aflatoxins are moderately stable during roasting processes and persist into finished foods, such as peanut butter (Scott, 1984). Roasting maize meal samples artificially contaminated with 5 ppb of FB_1 and naturally contaminated maize meal samples at 218 °C for 15 min resulted in 100% loss of fumonisins (Castelo et al., 1998). Pluyer, Ahmed, and Wei (1987) have reported that oven roasting of naturally contaminated peanuts at 150 °C for 30 min causes a 30–45% reduction in aflatoxin levels, with 48–61% reduction in AFB1 levels in artificially contaminated peanuts being achieved under the same conditions. It has been reported that roasting the maize flakes reduced fumonisin content to 6–35% (Meister, 2001). Fumonisin content in maize grits was reduced by approximately 70–76% after roasting for 5 min, while the roasting time of 2.5 min resulted in a reduction of only 20–60% (Lešnik et al., 2008).

Fermentation is an effective process to reduce the mycotoxin content due to enzymatic breakdown. During fermentation, a significant decrease in DON occurred of approximately 38–46% of the original content (Lancova et al., 2008). About 50% reduction in aflatoxin level in the wheat dough were observed by fermentation (Scott & Chełkowski, 1991). When the dough was fermented at 50 °C, the maximum reduction was 56% for the Vienna bread, with French bread being reduced by 41% (Samar, Neira, Resnik, & Pacin, 2001). Using contaminated grain for brewing, 2–7% of OT is delivered to beer after fermentation (Milani & Maleki, 2014).

Extrusion cooking reported to decreases the mycotoxins levels at rates depending on the type of extruder, the type of screw, the die configuration, the initial mycotoxin concentration, the barrel temperature, the screw speed, the moisture content of the raw material, and the use of additives. Kaushik (2015) reviewed the effect of extrusion cooking on the reduction of aflatoxin level was from 23 to 66% in peanut meal and 95% in cereals, 95% DON in maize flour. Thermal processing below 150 °C has little effect on fumonisin concentrations, but extrusion used extensively in the production of breakfast cereals and snack foods, substantially reduces fumonisin levels, especially in the presence of glucose. Extrusion reduced FB1 in contaminated maize grits by 64%–72% without glucose and 89%–94% with added glucose (Jackson et al., 2011). They also found extrusion alone resulted in 26%–73% reduction in the levels of fumonisin B2 and fumonisin B3, while levels of both mycotoxins were reduced by >89% in extruded maize grits containing 10% glucose. Extrusion cooking of maize at high temperatures (≥190 °C) reduces fumonisin concentrations in foods, with the amount of reduction achieved depending on cooking time, temperature, recipe, and other factors (Humpf & Voss, 2004). De Girolamo, Solfrizzo, and Visconti (2001) found about 60–70% of the initial amount of fumonisins were lost during the entire cycle of maize flake processing, with less than 30% losses occurring during the intermediate extrusion step (70–170 °C for 2–5 min).

5.6. Irradiation

Irradiation is usually classified as physical removal of mycotoxins; however, irradiation provides energy to chemicals and, thus, reactions occur and result in changes in molecular structures. Gamma and electron-beam irradiation have been evaluated for the

reduction of concentrations of trichothecenes in grains (He, Zhou, Young, Boland, & Scott, 2010). They reported that gamma-irradiation at a dose level of 6 kGy eliminated fungal flora in flour and wheat. Gamma-irradiation reduce greatly the natural occurrence of *fusarium* mycotoxins in bread (Aziz, Attia, & Farag, 1997). DON, ZEN, and T-2 toxin concentrations are reduced to 85, 20 and 2.0 μg/kg for wheat and to 125, 45, and 1.0 μg/kg for flour after 4 kGy exposure and a sharp drop in *Fusarium* toxin levels occurred at 6 kGy and was eliminated at 8 kGy (Aziz et al., 1997).

Aflatoxin production was increased in irradiated wheat grain but decreased in barley and maize when the grain was irradiated prior to inoculation (Paster & Bullerman, 1988). The effects of gamma irradiation on the degradation of aflatoxin B_1 in wheat, maize, and soybeans and of T-2 toxin in wheat, DON in soybeans, and ZEN in maize at 9, 13, and 17% moisture were studied by (Hooshmand & Klopfenstein, 1995). They also reported that irradiation doses of up to 20 kGy did not significantly affect aflatoxin B_1 in any of the three grains, but significant reductions occurred in T-2 toxin, DON, and ZEN concentration at doses of 10 or 20 kGy and in T-2 toxin at the 7.5 kGy dose. The energy required to break down DON and T-2 toxin in dry grains was higher than that of grains containing moisture. Most mycotoxins are not often affected by irradiation (He et al., 2010).

5.7. Chemical control

Fungistats like essential oils and anti-oxidants to prevent growth and mycotoxin accumulation in partially dried grain has been taken as an alternative method (Magan & Aldred, 2007). Essential oils will be obtained from plants and other natural products from bacteria and fungi to prevent mycotoxins.

Some essential oils such as cinnamon and clove leaf oil can control *Fusarium* species, *P. verrucosum* or *A. ochraceus* especially DON and OTA production depending on the environmental conditions (Cairns et al., 2003). Sumalan, Alexa, and Poiana (2013) found the inhibitory potential of essential oils on natural microflora and *Fusarium* mycotoxins production in wheat and recommended as natural preservatives for stored cereals. Magan (2006) reported tests on wheat grain, butyl hydroxy anisole (BHA), propyl paraben (PP), cinnamon oil and resveratrol gave greater than 90% reduction in DON and NIV accumulation.

Essential oils of Eugenia caryophyllata (clove tree) and Thymus vulgaris (thyme) were arrested *Aspergillus* species and aflatoxin B1 accumulation in stored peanut (Nesci, Montemarani, Passone, & Etcheverry, 2011). This report indicated that essential oil of thyme at 2000 and 3000 ppm were highly effective against *Oryzaephilus surinamensis* (L.) which is vector carrier of aflatoxigenic fungi, these concentrations gave 100% mortality. Aldred, Cairns-Fuller, and Magan (2008) found the efficacy of three essential oils (bay, clove and cinnamon oil) and the antioxidant resveratrol (0–500 ppm) on control of growth and OTA production by *Penicillium* and *Aspergillus* species on wheat grain. The result revealed that populations of the mycotoxigenic species and OTA contamination could be reduced by >60% by this treatment at the end of the storage period. Another study on wheat grain had showed that loss of OTA content by natural extracts obtained from grape pomace and grape seeds after 14 days was in the range 7.8–28.3% relative to the control sample, but increased up to 26.48–37% after 28 days while the highest loss in OTA content was recorded for treatment with grape pomace at the 500 ppm level (Alexa, Poiana, & Sumalan, 2012).

6. Conclusion

Mycotoxins are natural products of fungi occurring in grains. They have a detrimental effect on human health as well as economic loss. It can cause carcinogenic, mutagenic, and estrogenic in humans. The major mycotoxins contaminate grains are aflatoxin, fumonisin, DON, OT, and ZEN. Most of them can occur during storage due to improper storage conditions and storage structures. Grain harvesting at a time, proper drying and good storage conditions are the basic preventive mechanism for the growth of mycotoxins. Sanitation, screening, aeration and monitoring of stored grain are basic good management practice during storage. The use of some fungistats such as essential oils and antioxidants as well as grain processing like physical or mechanical, chemical, or thermal methods are important to reduce the concentration of mycotoxins in food.

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