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REVIEW

Aflatoxigenic fungi and mycotoxins in food: a review

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ABSTRACT
Food contamination is a common phenomenon in the production, distribution and consumption of processed and agricultural commodities all over the world. Food safety is now taking the frontal stage in food production, processing and distribution. This study assessed the presence of aflatoxigenic fungi and mycotoxins in foods, occurrence, control, socio-economic and health implications. This study also gave comprehensive information on the safety and mycological quality of foods as well the effect on the people and economy of various countries. The review revealed the various aflatoxigenic fungi in foods, their distribution in agricultural produce and their effects on reduction in yield and quality with attendant consumer health implications and resulting significant economic losses. In developing countries, majority of the people do not know the inherent dangers of consuming mouldy produce or food contaminated with fungi and moulds with possible contamination by mycotoxigenic fungi because of lack of awareness about the danger involved. In view of this, there is need for general and public education to sensitise the people on the economic and health hazards posed by mycotoxins. Control measures such as good agricultural practices, crop selection, proper washing and cooking practices of food commodities should be emphasized to the people. Regulatory control, fast and effective analyses and detection, good produce handling and storage should be encouraged as this will assist in mitigating the side effects of mycotoxins in foods particularly in the tropical and sub-tropical countries, and in Africa nations where there is enabling environment that promotes fungal growth, shortage of food and drought of modern storage and processing infrastructures.

KEYWORDS
Aflatoxigenic fungi; mycotoxins; foods; occurrence; control

Introduction

Fungi (*plural*, the *singular* noun is *fungus*) belong to the group of eukaryotic organisms which include yeasts, moulds and mushrooms (Moore, 1980, Hibbett et al., 2007). They are classified as a kingdom, Fungi, which differ from other eukaryotic life kingdoms of plants and animals (Hibbett et al., 2007).

Fungi are in a different kingdom from other plants, bacteria, and some protists due to the presence of chitin in their cell walls. This characteristic differentiates them from the likes of plants, bacteria, and some protists. Fungi are however, similar to animals because they are heterotrophs; possessing ability to absorb dissolved molecules digested through extracellular secretion of digestive enzymes into foods. Therefore, fungi do not have ability to produce their own food because they lack chlorophyll that is needed for photosynthetic processes (Hibbett et al., 2007).

Mycology is an emerging field of study which involves the study of fungi, fungal taxonomy, genetic and biochemical functions, and their use for food, medicinal and religious purposes and side effects of their secretions and metabolites (Struck, 2006).

Although some fungi are beneficial to man, however, several of them are known parasites to plants, animals (including man), and other fungi. Some fungi are pathogens to several crops causing extensive damage and agricultural losses. Common examples of fungal pathogens of importance are rice blast fungus Magnaporthe oryzae (Talbot, 2003), *Ophiostoma ulmi* and *Ophiostoma novo-ulmi* causing Dutch elm disease (Paoletti, et al., 2006) and *Cryphonectria parasitica* responsible for chestnut blight (Gryzenhout, *et al.*, 2006). Crop pathogens of importance belong to these genera *Fusarium*, *Ustilago*, *Alternaria*, and Cochliobolus (Paszkowski, 2006). Some fungi are carnivores feeding on other organisms as predators, examples are *Paecilomyces lilacinus*, which feeds on nematodes, capturing them with constricting rings or adhesive nets (Yang *et al.*, 2007). Several plant pathogenic fungi like *Phytophthora infestans*, could change from biotrophic i.e parasitic on living plants to necrotrophic i.e feeding on the dead tissues (Koeck, *et al.*, 2011).

Some fungi are pathogenic to man and are disease causing organisms in humans, some of the diseases caused by them could be fatal if not treated. Such diseases include aspergillosis, candidiasis, coccidioidomycosis, cryptococcosis,

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histoplasmosis, mycetomas, and paracoccidioidomycosis. Furthermore, immune-comprised people are particularly susceptible to disease by genera such as *Aspergillus*, *Candida*, Cryptoccocus (Hube, 2004, Nielsen and Heitman, 2007, Brakhage, 2005), Histoplasma (Kauffman, 2007), and Pneumocystis (Cushion, *et al.*, 2007). Some fungi are also responsible for infections of the eyes, nails, hair, and skin, especially the so-called dermatophytic and keratinophilic fungi, and cause ringworm and athlete's foot infections (Cook and Zumla, 2008). Many allergic reactions and allergies are caused by fungal spores and fungi from different taxonomic groups (Simon-Nobbe, *et al.*, 2008).

Uses of fungi

Human use

Fungi have been used extensively for preparation and preservation of foods and other culinary applications. Mushrooms contain no cholesterol and are eaten as a good source of protein. Mushroom farming has become large enterprises in many countries of the world. Fungi are being used for large scale production of antibiotics, vitamins, and anti-cancer and cholesterol-lowering drugs and other natural products of economic importance (Brakhage, *et al.*, 2004, Fincham, 1989). Through genetic engineering fungal metabolism has been modified in recent times (Fincham, 1989), for example, some yeast species have genetically modified (Hawkins and Smolke, 2008) to make them grow faster during fermentation which has tremendous impacts on food and pharmaceutical production and beverage industries worldwide (Brakhage, *et al.*, 2004).

Therapeutic uses

Many fungi produce metabolites that contain pharmacologically active drugs for treating man and animals. Among these important active ingredients are antibiotics, including the penicillins. However, artificial penicillins produced through chemical modifications of fungal synthesized penicillins have wider spectrum when compared with penicillin G (produced by *Penicillium chrysogenum*) with a narrower spectrum of biological activity. According to Pan, *et al.*, 2008, artificial penicillins are semisynthetic compounds which are gotten from fermentation cultures, and modified structurally to obtain specific desirable properties. Other antibiotics of importance produced by the same method are: ciclosporin, an immunosuppressant drug used in transplant surgery and fusidic acid, an antibiotic for controlling infection from methicillin-resistant *Staphylococcus aureus* bacteria (Fajardo and Martínez, 2008). Griseofulvin is also produced from *Penicillium griseofulvum* and for treating eczema, skin infections etc and other fungal infections (Manzoni and Rollini, 2002).

Traditional and folk medicine

Fungi are used in many Asian countries for traditional and folk medicine; certain mushrooms such as Agaricus subrufescens (Yuen and Gohel, 2005, Paterson, 2006), Ganoderma lucidum (Paterson, 2008), and Ophiocordyceps sinensis (Kulp, 2000) are used for treating different ailments in traditional Chinese medicine.

Cultured foods

In food processing, fungi have been used for centuries in baking. Saccharomyces cerevisiae or baker's yeast, a unicellular fungus, is used for production bread and other wheat-based products (Piskur, *et al.*, 2006). Also, yeast species of the genus *Saccharomyces* are used in fermentation processes to produce alcoholic beverages such beer, rum, stout etc. (Abe, *et al.*, 2006). In Asia, *Rhizopus* species are used for making tempeh from soybeans, a very important Asian food (Jørgensen, 2007).

In food

Mushrooms are sources of good quality proteins. Edible mushrooms could be cultivated or wildly grown. Several mushrooms are consumed in different ways, Commonly cultivated and edible mushrooms are Agaricus bisporus used in preparing salads, soups, and many other dishes in the West. Some African and Asian fungi such as straw mushrooms (*Volvariella volvacea*), oyster mushrooms (*Pleurotus ostreatus*), shiitakes (*Lentinula edodes*), and enokitake (*Flammulina* spp) (Erdogan *et al.*, 2003) are very common and are now commercially grown and eaten in the West.

Many other wild mushroom species are also commonly eaten (Orr and Orr, 1979). Examples are milk mushrooms, morels, chanterelles, truffles, black trumpets, and *porcini* mushrooms (*Boletus edulis*) (Orr and Orr, 1979).

Some fungal species are used to inoculate milk curds to give characteristic flavour and texture to the cheese and they are very important in cheese production. An example of such fungi is Penicillium roqueforti which imparts the characteristic blue colour to cheese with such as Roquefort cheese, by inoculating milk with the fungi (Kinsella and Hwang, 1976; Orr and Orr, 1979). Some moulds used to produce cheese are non-toxic and safe for human consumption but some species could produce mycotoxins like aflatoxins, roquefortine C, patulin which may accumulate as a result of growth of mixed culture of fungi during cheese ripening or storage (Kinsella and Hwang, 1976, Hachmeister and Fung, 1993).

Types of aflatoxigenic fungi

Aspergillus species are groups of moulds widely distributed all over the world. They can easily contaminate foodstuffs and animal feeds when conditions are favourable especially in the tropical and sub-tropical countries where relative humidity and temperature are very high. The genus

Table 1. Mycotoxins in staple grains and seeds.

Mycotoxin	Commodity	Fungal source(s)	Effects of ingestion	Reference
Deoxynivalenol/nivalenol	Wheat, maize, barley	*Fusarium graminearum Fusarium crookwellense Fusarium culmorum*	Human toxicoses in India, China, Japan, and Korea. Toxic to animals, especially pigs	(FAO 2004)
Zearalenone	Maize, wheat	*F. graminearum F. culmorum F. crookwellens*	Identified by the International Agency for Research on Cancer (IARC) as a possible human carcinogen. Affects reproductive system in female pigs	(FAO 2004)
Ochratoxin A	Barley, wheat, and many other commodities	*Aspergillus ochraceus Penicillium verrucosum*	Suspected by IARC as human carcinogen. Carcinogenic in laboratory animals and pigs	(FAO 2004)
Fumonisin B1	Maize	*Fusarium moniliforme plus several less common species*	Suspected by IARC as human carcinogen. Toxic to pigs and poultry. Cause of equine eucoencephalomalacia (ELEM), a fatal disease of horses	(FAO 2004)
Aflatoxin B1, B2 Aflatoxin B1, B2, G1, G2	Maize, peanuts, and many other commodities Maize, peanuts	*Aspergillus flavus* *Aspergillus parasiticus*	Aflatoxin B1, and naturally occurring mixtures of aflatoxins, identified as potent human carcinogens by IARC. Adverse effects in various animals, especially chickens	(FAO 2004)

Source: Adapted from Adeyeye (2016).

Aspergillus is an important mould in food processing and industrial food (Adejumo & Adejoro, 2014, Onions, *et al.*, 1981, Richard, 2007). *Aspergillus* species are moulds of importance in food spoilage. Spoilage due to contamination by *Aspergillus* species is responsible for changes like sensorial, nutritional and microbial such as pigmentation, discoloration, rotten, development of off odours and off flavours. Several *Aspergillus* species grew in foods very with low water activity and produced mycotoxins (Adejumo & Adejoro, 2014; Lee, et al., 2004). *Aspergillus niger* are common mould all over the world and with wide distribution on a variety of substrates. *Aspergillus niger* is the most common mould involve in post-harvest decay and losses of foods and agricultural produce (Ashiq, 2015, Pitt, et al., 2000).

Penicillium is also group of mould with wide distribution in foods and produce. Penicillium species have been found in fish and fish feed (Barbosa *et al.*, 2013). Some *Penicillium* species are responsible for producing toxic compounds like citrin and citreoviridin (Barbosa et al., 2013, Richard, 2007).

Fusarium is another mould of importance which affects foods and feeds. It is a field mould which is widely distributed worldwide. Common mycotoxins produced by Fusarium are deoxynivalenol and zearalenone (Barbosa *et al.*, 2013, Richard, 2007). Fusarium is a group of fungi of economic importance because they produce highly potent mycotoxins.

Mycotoxins produced by aflatoxigenic fungi

Mycotoxins are metabolites secreted by fungi growing on organic substrates of diverse nature which could produce fatal or side effects when ingested or consumed by humans or animals. Fatal effects could be vomiting, weight loss, tumors growth, and death. Several toxics secreted by fungi are well known, and majority of them occur in grain crops. Most mycotoxins affect organs in the body and could be fatal to blood, kidneys, skin, or central nervous system, and while some are known carcinogens (Ashiq, 2015; Yin, et al., 2008; Martins *et al.*, 2001).

Fungi are the major source of mycotoxins in foods. *Aspergillus*, *Penicillium*, and *Fusarium* are the fungi of greatest importance to humans with respect to food poison by mycotoxins. Aflatoxins are known as the most important fungal metabolites of a direct health hazard to humans. *Aspergillus flavus* is widely distributed in soil, air, and rotten plant residues. Aflatoxin production and contamination can take place in the field, in transit, or in storage. However, most infection takes places in the field while aflatoxin production takes place at any point under favourable conditions (Ashiq, 2015, Yin, et al., 2008, Martins *et al.*, 2001).

Major groups of mycotoxins in foods

Several toxigenic moulds have been identified, but only a few mycotoxin producing moulds, particularly those affecting cereals such as maize, wheat, barley, oats and rice and groundnuts are considered to be significant to human health (Bhat, *et al.*, 1989, Desjardins & Proctor, 2007, Jeswal & Kumar, 2015, Lewis *et al.*, 2005). Food contamination with mycotoxin could take place in the field as pre-harvest during growing period of crop plant or could occur after harvesting under favourable environmental conditions during processing, packaging, distribution, and storage (Pereira et al., 2014, Bhatnagar *et al.*, 2006). Mycotoxins contamination occurs in crops such as cereals, legumes and oil seeds (Table 1) that are stored under high temperature and high relative humidity for a prolonged time (Bennett, 2003). Aflatoxins are the most common among the various mycotoxins found in most of agricultural produce for human consumption and animal feed.

Aflatoxins are the most common mycotoxin and potent human hepatocarcinogen. Aflatoxin is produced in maize and groundnuts in the field under drought and in stored. It is produced by *A. flavus* and *A. parasiticus* in tropical and

Table 2. Mycotoxins in Human blood/serum from different countries.

Country	Sampling period	Mycotoxin	Total samples	Positive samples	Detection technique	Range (μg/L)	Reference
Argentina	2004–2005	OTA	435	274	HPLC	0.15–0.43	(Pacin, et al. 2008)
Chile	2004–2005	OTA	88	62	HPLC	0.07–2.75	(Munoz et al. 2006)
Croatia (Kaniza)	2004–2005	OTA	4343	24.6%	HPLC	2-50	(Radic et al. 1997)
Czech Republic	2004–2005	OTA	115	115	HPLC/ELISA	0.037–1.13	(Dohnal et al. 2013)
Czech Republic	2004–2005	OTA	2206	2077	HPLC	0.1–13.7	(Ostry et al. 2005)
Czech Republic	2004–2005	OTA	100	100	HPLC	0.1–0.35	(Malir et al. 2013)
Egypt	2006	AFB1–Alb	34	98	ELISA	3.0–35.1 pg/mg	(Piekkola et al. 2012)
Egypt	1999, 2004	AFB1–Alb	24	24	ELISA	n.d.–32.8 pg/mg	(Turner et al. 2008)
Egypt	–	Total AFs (B1, B2, G1, M1, B2a, G2a,AFL)	60	60	Two–dimensional TLC	0.37–1.11 (Kwashiorkor) 0.15–0.38 (Marasmus)	(Hatem et al. 2005)
Germany	1990–1997	O TA	102	100/95	EIA/ HPLC	0.072–1.290	(Martlbauer et al. 2009)
Germany	2005–2006	O TA	61	61	HPLC	0.07–0.75	(Degen, Mayer, and Blaszkewicz 2007)
Ghana	–	AFB1–Alb	24	24	RIA	0.1–4.44 pmol/mg	(Tang et al. 2009)
Ghana	–	AFB1–Alb	64	64	RIA	0.3325–2.2703 pmol/mg	(Jiang et al. 2005)
Ghana (Kumasi)	2006	AFB1–Alb	507	507	HPLC	0.44–268.73 pg/mg	(Shuaib et al. 2010)
Guinea	2002	AFB1–Alb	250	245	ELISA	Nd–66 pg/mg	(Turner et al. 2005)
Italy	2007	O TA	130	129	HPLC	0.084 – 4.835	(Biasucci et al. 2011)
Italy	–	AFG1	71	1	LC/MS/MS	3.48	(Ritieni et al. 2010)
Italy (Tuscany)	1994–1996	O TA	138	97%	HPLC	0.12–2.84	(Palli et al. 1999)
Italy (Tuscany)	–	O TA	6	6	HPLC	0.94–3.28	(Iavicoli et al. 2002)
Ivory Coast	2001 and 2004	O TA	102	30	HPLC	0.01–5.81	(Sangare Tigori et al. 2006)
Japan	1992,1994–1996	O TA	184	156	ELISA	4-278	(Ueno et al. 1998)
Kenya	2007	AFB1–Alb	597	78%	LC/MS/MS	<0.02-211pg/mg	(Yard et al. 2013)
Lebanon	–	O TA	250	33%	HPLC	0.1– 0.87	(Assaf et al. 2004)
Malaysia	2008	AFB1–Alb	170	97%	HPLC	0.2–23.16 pg/mg	(Leong et al. 2012)
Pakistan	–	O TA	96	87	HPLC	0.032–3.409	(Aslam et al. 2005)
Pakistan	–	O TA	127	107	HPLC	0.03 to 3.41	(Aslam et al. 2012)
Poland	2005	O TA	25	25	HPLC	0.19–3.77	(Grajewski et al. 2007)
		O TA		25		0.4–60	(Jonsyn-Ellis 2007)
		O TB		6		0.03–5.6	
		AFB1		23		0.2–74	
Sierra Leone	–	AFB2	131	5		0.02–2.2	
		AFG1		29	HPLC	0.3–56	
		AFG2		22		0.01–1.2	
		AFM1		39		0.03–6.8	
		AFM2		51		0.04–48	
		AFL		30		0.01–3.2	
		O TA		325	HPLC	0.06–10.92	
		AFB1–Alb	325	119	ELISA	4.8–260.8 pg/mg	
		AFB1–Alb	119	179	HPLC	27.8 – 77.4 pg/mg	
Spain (Lleida)	2008–2009	O TA	357	109	HPLC	<0.1–5.8	(Coronel et al. 2011)
The Gambia	2000	O TA	109	27.5%	HPLC	0.1– 11.98	(Turner et al. 2007)
The Gambia	1992	O TA	40	68	HPLC	0.12 – 1.5	(Wild et al. 2000)
Tunisia	–	O TA	68	37	ELISA	0.59 (mean)	(Grosso et al. 2003)
Tunisia	2005	AFB1	37	410	HPLC	0.08–2.29	(Ghali et al. 2008)
Tunisia	–	AFB2	484	266		0.01–0.67	(Khalifa et al.2012)
Turkey	–	AFG1	325	409		0.03–1.24	(Giray et al. 2009)
Turkey	2007–2008	AFG2		401		0.01–1.03	(Aydin et al. 2011)
Turkey (Isparta)	–	O TA	133	133	HPLC	0.19–5.5	(Ozçelik, Koşar, and Soysal2001)
UK		AFB1-Alb	104	95%	HPLC/ELISA	28.1 ± 14.6 (mean) pg/mg	(Turner et al. 1998)
USA	2007–2008	AFB1-Alb	170	20.6%	HPLC	1.01–16.57 pg/mg	(Johnson et al. 2010)
USA	1999–2000	AFB1-Alb	27	2016	LC–MS/MS	≥ 0.02–0.20	(Schleicher et al. 2013)

Source: Adapted from Waseem et al. (2014).

(Key: OTA,OTB: ochratoxin A,B; AFB1,AFB2,AFG1, AFG2,AFM1,AFM2: aflatoxin B1,B2,G1,G2,M1,M2; AFL: aflatoxicol; AFB1 -Alb: aflatoxin B1 albumin adduct; HPLC: high performance liquid chromatography; LC: liquid chromatography, TLC: thin layer chromatography; ELISA: enzyme linked immune-sorbent assay; MS: mass spectrometry; RIA: radioimmunoassay; EIA: enzyme immunoassay)

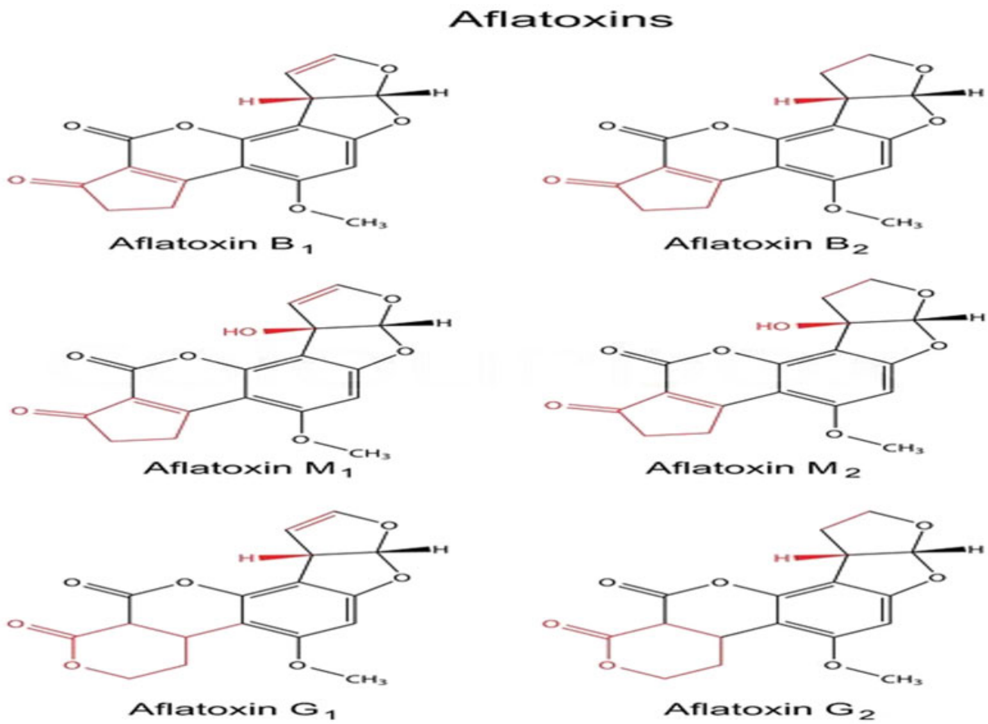

Figure 1. Structures of aflatoxins.

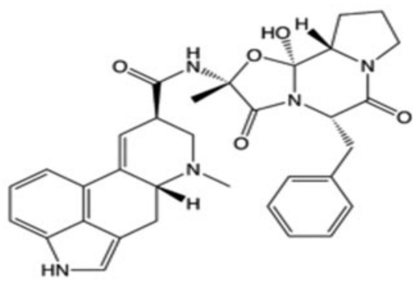

Figure 2. Ergotamine, a major mycotoxin produced by *Claviceps* species, which if ingested can cause gangrene, convulsions, and hallucinations.

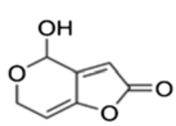

Figure 3. Structure of patulin.

sub-tropical countries because of favourable weather conditions (Desjardins & Proctor, 2007, Jeswal & Kumar, 2015). Aflatoxins are known carcinogenic secondary metabolites of fungal origin (Adejumo and Adejoro, 2014) and also rarely produced by *A. nominus and A. pseudotamari* (Adejumo and Adejoro, 2014, Mazaheri, 2009). Among the 18 different types of aflatoxins identified, the four naturally occurring ones are Aflatoxin B1 (AFB1), Aflatoxin B2 (AFB2), Aflatoxin G1 (AFG1) and Aflatoxin G2 (AFG2) (Adejumo and Adejoro, 2014, Filazi and Sireli, 2013). Aflatoxin B1 and B2 are identified by strong blue fluorescence under ultraviolet light (Table 2), hence the 'B', while Aflatoxin G1 and G2 are identified by greenish yellow fluorescence (Adejumo and Adejoro, 2014, Kensler *et al.*, 2011). Other aflatoxins metabolites are Aflatoxin M1 and M2 and they are commonly seen in foods of animal origin such as milk, eggs or blood of animals that are fed with AFB1 and AFB2-contaminated feed (Adejumo and Adejoro, 2014, IARC, 2002, CAST, 2003).

Several *species* of *Fusarium* have been to be toxigenic and of importance in human and animal health. *Fusarium graminearum,* the causal organism of head blight and ear rot in cereals, is responsible for the production of deoxynivalenol, zearalenone and fusarin C. In Eastern Europe human toxicoses caused by ingesting T-2 toxin and related compounds has been linked to *F. sporotrichioides.* (Bayman & Baker, 2006, Desjardins & Proctor, 2007, Jeswal & Kumar, 2015).

It has been reported severally epidemics of head blight and maize ear rot of *Fusarium* which are common in Asia, Africa and South America where cereals are predominantly grown. The high rates of oesophageal cancer in southern Africa and parts of China linked with the consumption of maize contaminated with fusarins and fumonisins from *F. moniliforme* are of great concern at the moment (Bhat et al., 1989, Desjardins & Proctor, 2007). Most of these mycotoxins produced by moulds that are of importance to human health are produced under poor storage conditions (Bhat et al., 1989, Desjardins & Proctor, 2007, Jeswal & Kumar, 2015, Adeyeye, 2016).

Aflatoxins are chemical metabolites and mycotoxins produced by *Aspergillus* species of fungi, like *A. flavus* and *A. parasiticus* (Adejumo & Adejoro, 2014, Ashiq, 2015, Martins, et al., 2001, Adeyeye, 2016). The common aflatoxins in foods and agricultural proce are (Figure 1) B1, B2, G1, and G2 (Yin, et al., 2008). Aflatoxin B1, the most toxic, is a potent carcinogen and has been directly correlated to adverse health effects, such as liver cancer, in many animal species (Ashiq, 2015, Martins *et al.*, 2001). Aflatoxins are

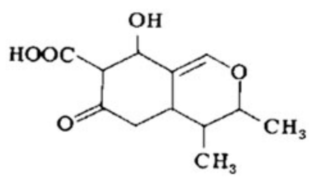

Figure 4. Structural formula of citrinin.

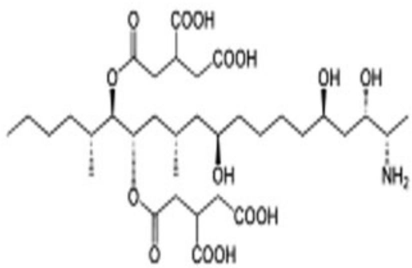

Figure 5. Structural formula of fumonisin B_1.

mycotoxins largely related to agricultural produce produced in the tropics and subtropics under humid climate, cereals, legume and oil seeds (Ashiq, 2015, Martins *et al.,* 2001; Yin *et al.,* 2008, Adeyeye, 2016).

Three forms of ochratoxin have been identified. These are A, B, and C produced by *Penicillium* and *Aspergillus* species (Adeyeye, 2016). The difference between them is that Ochratoxin B (OTB) is a non-chlorinated form of Ochratoxin A (OTA) while Ochratoxin C (OTC) is an ethyl ester form Ochratoxin A (Ashiq, 2015, Bayman & Baker, 2006, Jeswal & Kumar, 2015, Adeyeye, 2016). Several *species* of *Aspergillus* have been implicated in secretion of ochratoxin. These include *Aspergillus ochraceus* responsible for contamination of beverages like beer and wine. *Aspergillus carbonarius* responsible for vine fruit contamination especially during juice making process. Ochratoxin A is a known carcinogen and nephrotoxin. Its activities have been seen as responsible for tumors in the human urinary tract but this needs further investigation (Ashiq, 2015, Bayman & Baker, 2006, Jeswal & Kumar, 2015, Adeyeye, 2016).

Citrinin has been detected *P. citrinum*, but currently several species of *Penicillium* and *Aspergillus* is implicated. Common ones among them is *Penicillium camemberti* used for cheese making and *Aspergillus oryzae* used for production of sake, miso, and soy sauce. Citrinin has been identified in yellowed rice disease in Japan and as a nephrotoxin in laboratory animals (Bennett & Klich, 2003, Adeyeye, 2016). Citrinin is widely linked with agricultural produce such as wheat, rice, corn, barley, oats, rye, and food coloured with Monascus pigment. Citrinin has been found to act synergistically with Ochratoxin A to depress RNA synthesis in murine kidneys but its side effects in human health is unknown. (Ashiq, 2015, Bennett & Klich, 2003, Jeswal & Kumar, 2015, Adeyeye, 2016).

Ergot has been detected as a toxin in the sclerotia of species of *Claviceps*. *Claviceps* infected cereals and consumption of cereal contaminated by ergot sclerotia especially bread produced from contaminated flour caused ergotism, a disease commonly referred to as St. Anthony's fire. Good agricultural practices with modern storage techniques have eliminated ergotism as a human disease; but are still important in animal feed production. Ergot alkaloids are of importance in pharmaceutical industries (Ashiq, 2015, Bennett & Klich, 2003, Jeswal & Kumar, 2015).

Patulin has been isolated from *P. expansum*, *Aspergillus*, *Penicillium*, and *Paecilomyces* fungal species. *P. expansum* has been linked to moldy fruits and vegetables, especially rotting apples and Figs. (Moss, 2008, Trucksess & Scott, 2008, Adeyeye, 2016). However, fermentation process has been found to destroy it as it is not usually detected in apple beverages like cider. Patulin is non-carcinogenic but it has been implicated to damage the immune system of animals (Moss, 2008, Adeyeye, 2016).

Fusarium toxins have been detected developing cereal grains like maize, wheat etc and about 50 species of *Fusarium* have been implicated (Schaafsma & Hooker, 2007). Mycotoxins of importance from Fusarium are fumonisins, implicated in horses' nervous disorders and a proven carcinogen in rodents; trichothecenes, are known as causal of chronic and fatal toxicoses in animals and humans; and zearalenone, is not known for any fatal toxic effects in animals or humans. Other *Fusarium* toxins of importance are: beauvercin and enniatins, butenolide, equisetin, and fusarins (Desjardins & Proctor, 2007, Adeyeye, 2016).

Health implications of eaten foods contaminated by mycotoxins

Mycotoxins are chemical metabolites of great economic importance and health implication to both animals and humans.

Aflatoxin ingestion has been implicated in hepatocellular carcinoma (liver cancer) (Adejumo and Adejoro, 2014, Williams et al., 2004), reported to be the third-leading cause of cancer worldwide according to WHO (2008), with about 600,000 fresh cases each year. Adejumo and Adejoro, 2014, Hussein and Brussel, 2001 and Zain, 2011 have reported that aflatoxin contamination reduces feed intake, increase liver and kidney weights of farm animals, as well as induce immune-suppression and hepatitis as well as high mortality in farm animals.

Mycotoxins have been implicated in several countries for the outbreak of diseases. In India and Kenya mycotoxins have been implicated in the outbreak of aflatoxic hepatitis, in the outbreak of enteric ergotism in India; in the outbreak of vascular ergotism in Ethiopia; and in the outbreak of deoxynivalenol mycotoxicosis in India and China. The outbreaks have been linked to consumption of cereals that were grown and stored under drought and humid conditions during either the growing season or harvest or storage (Jelinek et al., 1989).

Aflatoxins among all the mycotoxins were linked to human diseases such as liver cancer, Reye's syndrome, Indian childhood cirrhosis, chronic gastritis and kwashiorkor in many parts of the world, particularly in African and Asian countries where conditions for growth and storage

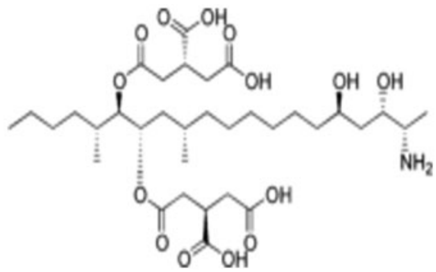

Figure 6. Structural formula of fumonisin B_2.

encouraged fungi and mycotoxin production (Jelinek *et al.,* 1989, Palmgren & Hayes, 1987, Adeyeye, 2016).

Kenya recorded a serious and largest and most acute outbreaks of aflatoxicosis ever documented (CAST, 2003) in 2004, with125 dead cases and over 317 others hospitalized for consuming aflatoxin-contaminated maize (Adeyeye, 2016). The nature of the outbreak was due to the consumption of maize contaminated with extremely toxic AFB1. The case-control studies carried out by Lewis *et al.,* (2005) showed that the affected people in the area consumed home-grown maize stored under humid conditions. During the outbreak, AFB1 individual daily exposure was 50mg/day (Probst *et al.,* 2007).

Several like Kashin Beck syndrome in the USSR, China and Viet Nam; Mseleni joint disease in southern Africa; endemic familial arthritis in India; alimentary toxic aleukia in the USSR; and oesophageal cancer in southern Africa were linked to *Fusarium* toxins. Also, Balkan endemic nephropathy and urinary tract tumours have been linked to Ochratoxins (Berry, 1988, Adeyeye, 2016).

Economic implications of mycotoxins in foods

According to FAO, 1988, volume of global trade in agricultural produce like wheat, rice, barley, corn, sorghum, soybeans, groundnuts and oilseeds totalling several millions of tonnes on yearly basis. Agricultural produce are contaminated by mycotoxins due to unhygienic post-harvest handling of the crops and poor agricultural practices. Financial losses from mycotoxin-contamination of agricultural produce could be subjective, staggering and very difficult to obtain. Several other losses from mycotoxin contamination may include lower productivity; losses of foreign exchange earnings; costs involved in inspection, sampling and analysis of produce before and after shipments, all these could be large; losses to compensation paid in case of claims; farmers' subsidies to cover production losses; research, training and extension programme; costs of detoxification etc. could also be enormous when added together (Coulibaly, 1989, Adeyeye, 2016).

Economic impacts of mycotoxins on crops are very important, particularly cereals like wheat, maize, legumes like cowpea and groundnuts. According to Schmale III and Munkvold, (2018) over 25% of global harvest are involved on yearly basis, with total losses of 1 billion metric tons of foods and food products annually. The economic losses are as consequence of 1) crop yield losses as a result of toxigenic fungi infestation; 2) value reduction due to mycotoxin contamination of crop; 3) animal productivity reduction due to mycotoxin-related animal health problems; and 4) costs of human health problems. Schmale III and Munkvold, (2018) also reported prevention, sampling, mitigation, litigation, and research costs.

Several researchers (Schmale III and Munkvold, 2018, Shephard, 2008, Richard, 2007, Munkvold, 2003) agreed that the economic impacts of mycotoxin contamination are felt by all stakeholders in food chain systems because of health care impacts and productivity losses. Schmale III and Munkvold, 2018 and Munkvold, 2003 estimated the costs of mycotoxins on produce in the USA and Canada annually to \$5 billion. However, this estimate does not include human health impacts or crop yield losses. They also estimated cost of aflatoxins in maize in the United States annually to \$225 million excluding costs of mitigation costs. The costs of aflatoxins in United States peanuts according to Schmale III and Munkvold, 2018 ranged over \$25.8 million losses per year between 1993 to 1996. Schmale III and Munkvold, 2018 also valued economic losses due to deoxynivalenol in the U.S.A to \$655 million annually, with the largest occurring in wheat. In developing countries, however, conflicting values are available, but according to Shephard, 2008 due to high aflatoxins contamination levels in the developing countries; economic losses may be far more than those obtaining in the United States. Shephard, 2008 revealed that economic losses in the three Asian countries of Indonesia, Philippines, and Thailand because of aflatoxins contamination exceeded \$900 million/year.

Prevention and control of mycotoxins in foods

In several countries of the world, some preventive steps to reduce mycotoxin contamination in agricultural produce have been taken. The preventive measures are as follows:

Crop breeding

The contamination of produce could be reduced drastically to the barest minimum through effective crop breeding. By selection and adoption of mycotoxigenic fungi resistant crop varieties, mycotoxin contamination of the produce from the field could be drastically reduced. The adoption of this method has been used to reduce the problem of ergot contamination of cereals such as rye, wheat and pearl millet that are resistant to mycotoxigenic fungi. However, little success has been achieved in using the method to reduce aflatoxins contamination of corn and peanuts (Fox & Howlett, 2008, Jelinek *et al.,* 1989, Adeyeye, 2016).

Good Agricultural Practice

Aflatoxigenic fungi infestation on crops and subsequent mycotoxin formation in agricultural produce could be minimized during production and before harvest through adoption of good agricultural practices like crop rotation, farm irrigation, adequate weed control, adoption of mould-resistant crop varieties, and use of bio-control like use of non-mycotoxigenic fungal strains.

Crop Rotation

This is a cropping system that encourages farmers not plant crops that belong to the same family to follow each in a rotation. Crops that are affected by same toxigenic fungi should not be allowed to follow each other in a rotation. For example, wheat and maize that are highly susceptible to toxigenic Fusarium spp, attack should not be allowed to follow each other in a rotation system (Adejumo and Adejoro, 2014, CAC, 2003, Munkvold, 2003).

Sanitation

In order to eliminate attack by toxigenic fungi on the produce, hygienic removal, destruction and disposal of wastes of previous harvested crops will assist in reducing toxigenic fungi contamination of the produce from the field (Adejumo and Adejoro, 2014). Cleaning of the stores and proper disinfection with appropriate fungicides before storing new produce has been found to reduce mycotoxin contamination of produce (Adejumo and Adejoro, 2014, Adeyeye, 2016, Hell *et al.*, 2000).

Insect Management

Insect infestation and damages could be sources of entry for toxigenc fungi into the produce. According to Bankole and Adebanjo, 2003, the extent of mycotoxins contamination of produce could be determined by the level of insect damage of the produce. Insect damage has been found to be a good entry point for Fusarium mycotoxins contamination of maize grains (Adejumo and Adejoro, 2014, Avantaggio *et al.*, 2002). Insects could carry spores of mycotoxigenic fungi from crop surfaces to the interior of the produce through created wounds as a result of their feeding habits and thereby promoting mycotoxin contamination of produce (Adejumo and Adejoro, 2014, Munkvold, 2003, Ariyo *et al.*, 2013). Good pest control system could be an appropriate way to reduce mycotoxins contamination.

Proper Irrigation and Fertilization

Mycotoxin development in produce has been linked to water stress during crop production. Adoption of irrigation and proper fertilization during crop production could reduce plants' stress which is sometimes responsible for mycotoxin development in produce. It has been reported that applying fertilizer and other soil conditioners to the soil to give adequate soil pH and enough plant nutrients are critical in mitigating against mycotoxin development in produce (Adejumo and Adejoro, 2014; CAC RC, 2003, Munkvold, 2003).

Early harvesting

Fungal infection of crops in the field as well as post-harvest contamination of the harvested produce is greatly minimized by early harvesting. In Nigeria, unpredictable weather, lack of good storage facilities and space, labour constraint, farmers' financial need, attacks by rodents and thieves are among factors that force farmers to harvest their produce at inappropriate times (Amyot, 1983). Early harvesting and threshing of groundnuts have been found to reduce aflatoxin levels and increase gross returns on produce than in delayed harvesting according to Rachaputi *et al.*, (2002).

Proper drying

Several researchers (Adejumo and Adejoro, 2014, Lanyasunya *et al.*, 2005, Ariyo *et al.*, 2013) revealed that proper and quick dehydration of produce to reduced moisture content is critical to reducing mycotoxin contamination of agricultural produce by creating unfavourable conditions for fungal growth and reproduction, insect attack and preserves produce longer. Rapid drying immediately after harvest has been found to mitigate against secretion of mycotoxins by fungi in produce. According to Ariyo *et al.*, 2013 and Adejumo and Adejoro, 2014, reported that reducing the water activity (aw) of produce to about 0.7 by reducing water content produce and maintaining produce below 0.7 aw is an effective way to control fungal spoilage and mycotoxin production in agricultural produce.

Reducing mycotoxins contaminations through postharvest steps include quick dehydration by mechanical means and maintaining crops in dried form. Sorting out contaminated produce by physical means, colour and proper washing with water have been found to reduce mycotoxins in produce.

Chemical methods of detoxification include ammoniation processes. Detoxification of aflatoxins in produce has been tried by many countries such as Senegal However, detoxification procedure should involve safety and efficacy tests for good result but this will surely increase handling costs (Fox & Howlett, 2008, Jelinek *et al.*, 1989).

According to Adejumo and Adejoro, 2014, several developing countries have undertaken some successful steps and measures to control mycotoxins like contaminated peanuts segregation in Malawi, peanut meal detoxification for export in Senegal, mycotoxins regulation in animal feed in Zimbabwe, adoption of resistant peanut varieties less susceptible to aflatoxin contamination in Burkina Faso, better produce-handling practices in Nigeria during the 1960s and in The Gambia during the 1990s.

Physical Separation

Mycotoxin contamination in produce could be minimized through physical treatments by sorting, winnowing, washing, crushing and de-hulling to remove moulds and infested grains and thereby reducing mycotoxin concentration in the produce (Adejumo and Adejoro, 2014, Fandohan *et al.*, 2005).

Biological Control

Mycotoxins are biologically controlled by using non- mycotoxigenic microorganisms to compete for space and nutrients, production of anti-mycotoxigenic metabolites by co-existing with mycotoxigenic microorganisms. Substratum pH changes coupled with a combination of other factors such as use of bio-control have been found to be effective in controlling fungal infestation and mycotoxin contamination in produce (Adejumo and Adejoro, 2014, Bianchini and Bullerman, 2010). Dorner and Cole (2002) and Adejumo and Adejoro, 2014 reported that post-harvest contamination of aflatoxins was minimized by a field application of non-toxigenic strains of *A. flavus* and *A. parasiticus*.

Legislations

Legislations relating to mycotoxins have been introduced by several countries. However, attentions in those nations have been shifted to the major mycotoxins like aflatoxins, ergot alkaloids, deoxynivalenol and ochratoxins. Most of these legislative measures are yet to be harmonized but Codex Alimentarius Commission is making concerted efforts to establish international guidelines and rules to guide the amounts of mycotoxins, and aflatoxins in particular permissible in produce (Fox & Howlett, 2008, Jelinek *et al.,* 1989).

Implementation of mycotoxin control measures have been undertaken for agricultural produce involving in international export or in countries with large-scale buying and distribution systems for international trade. However, in many developing countries especially in Africa, where food production and consumption involved subsistence agriculture greater percentage of the population, such measures would be very difficult to implement (Adeyeye, 2016, Fox and Howlett, 2008, Jelinek *et al.,* 1989).

According to Adejumo and Adejoro, 2014, "the Codex Alimentarius Standard on aflatoxin limits are 0.05 µg/l for milk and milk products, 4 to 5 µg/kg for beans, 10 µg/kg in nuts such as peanuts and almonds, and 20 µg/kg for cereals. The acceptable limit for fumonisins is $\leq$1000 µg/kg (Adejumo and Adejoro, 2014, CAST, 2003). These limits are also adopted in Nigeria (Adejumo and Adejoro, 2014). Also, Adejumo and Adejoro, 2014 stated that the EU limit for OTA in raw cereal is 0.5 µg/kg, with a tolerable weekly intake (TWI) of 0.12 µg/kg, while maximum DON limits are 200 µg/kg for processed cereal based foods and baby infants formula and foods for young children, and 1750 µg/kg for unprocessed wheat, oats and maize (Adejumo and Adejoro, 2014, EC, 2006).

Apart from the above intervention strategies, Atanda *et al.,* (2013) recommended the following mycotoxins control strategies in Nigeria: a database collection of predominant fungi and mycotoxin in Nigeria, a mycotoxin occurrence map establishment to know the areas susceptible to mycotoxin contamination and a permanent culture collection media establishment (Adejumo and Adejoro, 2014). They believed that these strategies will reduce mycotoxin infection and reduce cancer prevalence in Nigeria.

Conclusions

Fungi are very important organisms and their usefulness and economic importance cannot be overstated. However, many of them produced metabolites that are poisonous or dangerous to humans and animals. These metabolites are called mycotoxins. Mycotoxins are important because their implications in animal and human health are substantial and the economic importance widely studied. This review has shown the occurrence of mycotoxins in foods and feed in Nigeria and many parts of the world. Unfortunately, majority of the populace in these developing countries do not know the inherent dangers of consuming mouldy produce with possible contamination by mycotoxigenic fungi because of lack of awareness about the danger involved. In view of this, there is need for general and public education to sensitise the people on the economic and health hazards posed by mycotoxins. Control measures such as physical selection, proper washing and cooking practices of food commodities should be emphasized. Regulatory control, quick and effective analyses and detection, good produce handling and storage should be encouraged as this will assist in minimizing the side effects of mycotoxins contamination of foods especially in Africa where there is enabling environment for the growth of mycotoxigenic fungi, shortage of food and draught of modern storage and processing infrastructures.

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