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Current Opinion in Food Science

Prevalence of mycotoxins in foods and decontamination

Andrea Patriarca and Virginia Fernández Pinto

Toxigenic fungi can colonize crops and may accumulate bioactive substances in the infected products. These compounds, called mycotoxins, occur widely in nature and pose a great risk to human and animal health. The most relevant toxigenic fungal species belong to the genera *Aspergillus*, *Penicillium*, *Alternaria* and *Fusarium*. Mycotoxins are produced naturally in many agricultural crops. They can accumulate in food commodities in the field, after harvest, and during storage. Most of the important mycotoxins are resistant to most forms of food and feed processing. Several efforts are made to reduce mycotoxins in raw materials and processed food, both in pre-harvest stages inhibiting production of the toxins in the field, and in post-harvest by remediation strategies, reducing mycotoxin concentration in commodities.

Address
Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Química Orgánica, CONICET, Instituto Nacional de Micología y Botánica (INMIBO), Buenos Aires, Argentina

Corresponding author: Patriarca, Andrea (andreap@qo.fcen.uba.ar)

Current Opinion in Food Science 2017, **14**:50–60

This review comes from a themed issue on **Food microbiology**

Edited by **Ursula Barron-Gonzales**

http://dx.doi.org/10.1016/j.cofs.2017.01.011

Introduction

Toxigenic fungi can colonize crops and in favourable environmental conditions cause enormous economic losses due to the deterioration of the vegetables in pre-harvest, postharvest and storage stages. They may accumulate a large quantity of bioactive substances, called secondary metabolites, in the infected products. These metabolites are not essential for the growth and reproduction of the organism that synthesizes them and each fungal species has a profile of secondary metabolites of its own. While many of these compounds may be beneficial, others, called mycotoxins, pose a great risk to human and animal health because of the adverse effects that their contact or ingestion causes.

Contamination of food with mycotoxins is the result of the interaction between the microorganism producing the toxin, the substrate that may be susceptible to a greater or lesser extent, and the environment [1]. Physical factors such as moisture and available water, temperature, physical integrity of the grain or plant tissue, and chemical factors, like substrate composition, pH, mineral nutrients, and oxygen availability, influence mycotoxin accumulation.

From the point of view of food contamination, the most relevant species belong to the genera *Aspergillus*, *Penicillium*, *Alternaria* and *Fusarium*. Some of them cause deterioration typically during storage (*Aspergillus* and *Penicillium*), while others (*Alternaria* and *Fusarium*) are plant pathogens, generally with host specificity, causing contamination and consequent accumulation of toxin in the pre-harvest stage.

The contamination of a food matrix with different fungal strains could mean the accumulation of more than one mycotoxin. Moreover, a single fungal strain may be able to produce a wide spectrum of structurally different mycotoxins. Synergistic, additive, less than additive, or antagonistic toxicological effects among the different toxins might occur, implying, in some cases, an even higher risk for consumers than initially estimated [2].

Some mycotoxins are notable for their high toxicity, such as aflatoxins that are among the most potent natural hepatocancerigens known so far; others may affect the kidney (ochratoxin A, citrinin), the gastrointestinal system (deoxynivalenol, patulin), or the reproductive system (zearalenone). Some have multiple toxic effects in man and animals (trichothecenes) or are most likely associated with high incidence of esophageal cancer in certain populations (fumonisins and *Alternaria* toxins) [1,3,4••]. Table 1 summarizes the major mycotoxins in foods, main producing fungal species, most susceptible crops and their effects on human and animal health (Figures 1 and 2).

Fungal growth and mycotoxin production is markedly affected by environmental factors, especially temperature and humidity. Thus the accumulation of mycotoxins both before and after harvest largely reflects climatic conditions [5]. In general, the crops in tropical and subtropical areas with high humidity and temperature are susceptible to contamination by the most dangerous mycotoxins [5,6].

Mycotoxin contamination in various crops is of major concern, both for its implications on human and animal

Table 1

Major mycotoxins, producing fungal species, most frequently contaminated food, and human/animal related diseases

Mycotoxin	Producing fungi	Susceptible food	Main disease/symptoms
AF	*Aspergillus flavus*, *A. parasiticus*	Maize, peanuts, tree nuts, rice, figs	Liver lesions, hepatocellular carcinoma
OTA	*Aspergillus* section *Nigri*, *A. ochraceus*, *Penicillium verrucosum*	Cereals, coffee, cocoa, dried vine fruit, wine	Endemic nephropathy, urothelial tumours
ZEA	*F. culmorum*, *F. equiseti*, *F. verticillioides*, *F. graminearum*	Maize, barley, wheat, rye	Estrogenic effects, cervical cancer
FUM	*F. proliferatum*, *F. verticillioides*	Maize, sorghum	Esophageal carcinoma, equine encephalomalacia pulmonary edema
T-2, HT-2	*F. langsethiae*, *F. poae*, *F. sporotrichioides*	Wheat, maize	Alimentary toxic aleukia
DON	*Fusarium graminearum*, *F. poae*, *F. culmorum*, *F. crookwellense*, *F. sporotrichioides*, *F. tricinctum*, *F. acuminatum*	Wheat, maize, barley, oat, rye	Nausea, vomiting, diarrhea, abdominal pain, feed refusal
NIV	*F. crookwellense*, *F. poae*, *F. nivale*, *F. culmorum*, *F. graminearum*	Wheat, maize, barley, oat, rye	Erythropenia, leucopenia, hematotoxicity
PAT	*P. expansum*	Apples, pears, fruit by-products	Damage of gastrointestinal and respiratory systems
AOH, AME	*Alternaria alternata*, *A. tenuissima*, *A. arborescens*	Tomato and tomato products, fruit and fruit products, cereals, wine, beer	Mutagenic, esophageal cancer
TeA	*A. tenuissima*, *A. arborescens*	Tomato and tomato products, fruit and fruit products, cereals, wine, beer	Haematological disorder
ATXs	*Alternaria alternata*, *A. tenuissima*, *A. arborescens*	Wheat, rice, sunflower seeds	Mutagenic effects

AF, aflatoxins; AME, alternariol methyl ether; AOH, alternariol; ATXs, altertoxins; DON, deoxynivalenol; FUM, fumonisins; HT-2, HT-2 toxin; NIV, nivalenol; OTA, Ochratoxin A; PAT, Patulin; T-2, T-2 toxin; TeA, Tenuazonic acid; ZEA, zearalenone.

health and the substantial economic losses that their presence causes in food and feed industry. The Food and Agriculture Organization (FAO) estimated that 25% of the world's yearly crop production is contaminated with mycotoxins, leading to annual losses in food and feed products of estimated 1 billion metric tons [7]. The total costs of mycotoxin contamination can be attributed to reduced yields, food and feed losses, depreciated crop value, reduction in animal productivity, rise of human and animal medical expenses, prevention, control and detoxification investments, and increased costs for inspection and analyses, among others [8,9].

These highly toxic compounds can be present throughout the dietary chain, from staples to processed foods, since are commonly resistant to a wide spectrum of environmental factors or process treatments. They are stabile at high temperatures and at low pH values typical of the gastric juice of animals [8]. Maximum levels for major mycotoxins allowed in food have been established worldwide for domestic commerce and international trade.

This review covers the problem of mycotoxin contamination in foods, including main mycotoxins, their prevalence in susceptible foods, human and animal health impacts, and decontamination methods.

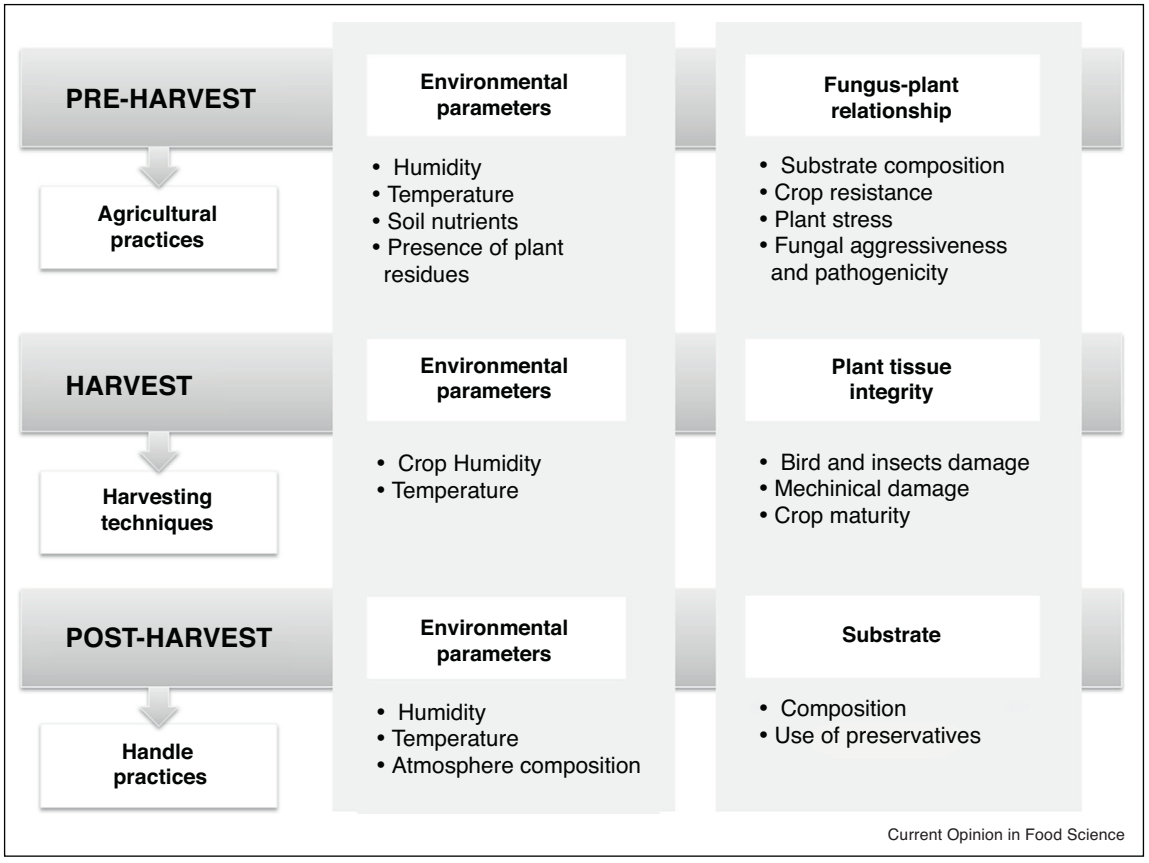
Aflatoxins

Aflatoxins (AF) are difuranocoumarin derivatives synthesized by a polyketide pathway by fungal species from *Aspergillus* section *Flavi*, mainly *A. flavus* and *A. parasiticus*. These toxins were the first mycotoxins discovered in the early 1960s as the causative agent of the turkey X disease epidemic, which resulted in the deaths of thousands of turkey poults, ducklings, and chicks fed a toxic peanut meal [4••].

Aflatoxins B_1, B_2, G_1, and G_2 are naturally biosynthesized, while AFM_1 is the predominant metabolite of AFB_1 in milk from lactating humans and animals that consume AFB_1-contaminated food or feed. Aflatoxin B_1 is a well-known human carcinogen [10]. Simultaneous AFB_1 and hepatitis B infections commonly occur in regions with high rates of hepatocellular carcinoma (HCC) [6], and numerous cases of acute aflatoxicosis in humans have been reported in some economically developing countries [4••].

The presence of these mycotoxins has been reported in a wide variety of food commodities, being peanuts, maize and tree nuts the most susceptible crops. Other frequently contaminated products are rice, cottonseed, Brazil nuts, spices, and figs [6] (Table 2). Aflatoxins are of major concern in tropical and subtropical climates, especially in developing countries where safe food storage is not guaranteed [11]. Optimal conditions for their production are high temperature and humidity (30–33°C, 0.99 water activity (a_w)) [52]. Specific limits have been set in a high number of countries and they range from 0 to 30 μg/kg for aflatoxin B_1 in foodstuffs and from 0 to 50 μg/kg for total aflatoxins.

Figure 1



Factors influencing mycotoxin accumulation in food.

Ochratoxin A

Ochratoxin A (OTA) is a pentaketide derived from the dihydrocoumarins family coupled to β-phenylalanine that was discovered as a metabolite of *A. ochraceus* in 1965. Afterwards, it was found that several *Aspergillus* and *Penicillium* species could also synthesize this toxin, *A. alliaceus*, *A. auricomus*, *A. carbonarius*, *A. glaucus*, *A. melleus*, *A. niger*, and *P. verrucosum* among them [6].

OTA is nephrotoxic to all animal species studied to date and to humans, and it has been related to the Balkan endemic nephropathy [10,12]. It has shown immunosuppressive, teratogenic and carcinogenic properties, and it has been detected in blood and other animal tissues and in milk, including human milk.

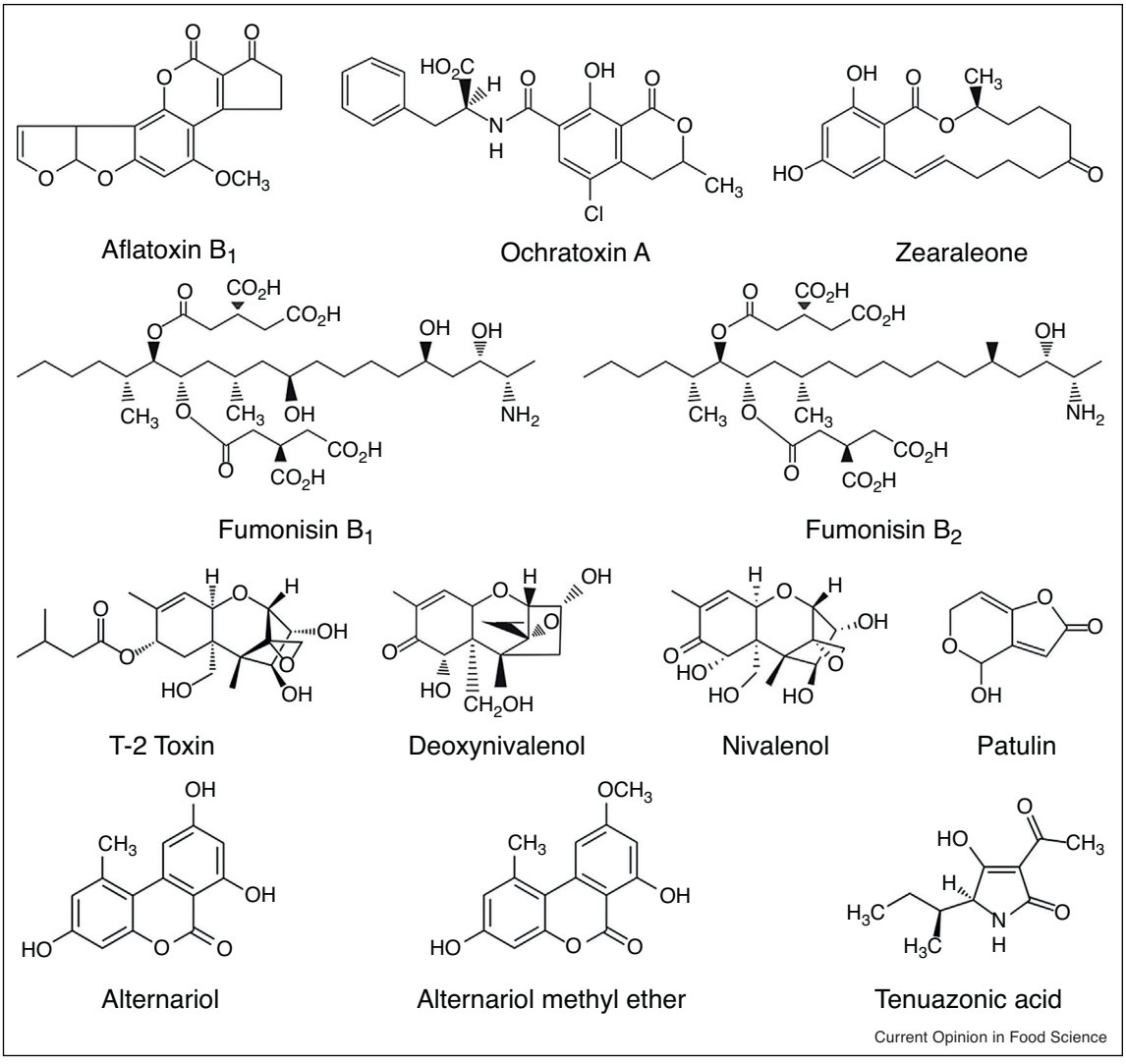
Ochratoxin A has been found in cereals, such as barley, rye, wheat, in coffee and cocoa beans, rice, dried fruits, spices, and other plant products, with barley having a particularly high likelihood of contamination worldwide [6,11]. It can also be present in by-products, like wine, beer or coffee, since it is not destructed during most food processes (Table 2).

Optimal environmental conditions for OTA production are quite variable and dependent on the producing fungal species. In general high to temperate temperatures (25–37°C) and high to moderate humidity (0.94–0.98 a_w) favours the accumulation of this toxin [13,14]. The European Union have established maximum limits for Ochratoxin A in a wide range of foodstuffs, from cereals to dried vine fruits, coffee beans, soluble coffee, wine, grape juice, beer, cocoa and cocoa products, meat products, spices, processed cereal-based foods, baby foods for infants, and dietary foods for special medical purposes, in values that range from 0.5 to 10 μg/kg [15]. Other countries, such as China only have set limits in grains and by-products (5.0 μg/kg) [16].

Zearalenone

Zearalenone (ZEA) is an estrogenic lactone of the resolsyilic acid synthesized by various *Fusarium* species; *F. graminearum* is the main producing one. Zearalenone causes estrogenic effects in animals and some studies have linked ZEA with the stimulation of human breast cancer cells growth. ZEA is rapidly excreted so it does not

Figure 2



Chemical structures of relevant foodborne mycotoxins.

accumulate in meat or eggs but can be excreted into milk when it is fed at high doses to lactating cows [17••].

Corn is the most susceptible crop to zearalenone contamination, but wheat, barley, oat and rye can also accumulate significant levels of this toxin (Table 2). High accumulation in grains occurs at wet temperate weather at preharvest stages and improper storage in high moisture environments (opt. 25°C, 0.96 a_w) [4••,17••,18•,52].

Limits for zearalenone in maize and other cereals currently vary from 20 to 1000 μg/kg worldwide.

Fumonisins

Fumonisins (FUM) consist of a long chain hidrocarbon backbone similar to that of sphinganine. Six fumonisins have been identified, FA_1, FA_2, FB_1, FB_2, FB_3, FB_4. FB_1 is the most toxic and prevalent in cereals, mainly in corn.

FUM have been known as secondary metabolites from several *Fusarium* species, such as *F. proliferatum* and *F. verticilloides*. However, more recently, these toxins have been detected in cultures of *Aspergillus niger*. As this is a widely occurring species and important industrial organism, FUM production by this fungus has an important implication for food safety [19].

Equine leukoencephalomalacia, porcine pulmonary edema and hepatic and renal injury are associated with comsuption of feed contaminated with FUM. These toxins are cytotoxic and carcinogenic to animals. FB_1 has been associated with esophageal cancer in humans in China and South Africa [4••,17••,18•].

Table 2

Concentration levels reported for main mycotoxins in foods

Mycotoxin	Food	Range (μg/kg or μg/L)[a]	Reference
AF	Maize	0.02–46000	[6,56,57]
	Peanut and products	0.3–329000	
	Hazelnut	25–175	
	Walnut	15–25	
	Pistachio nuts	15–259	
	Brazil nuts	1.2–11.9	
	Rice	0.1–308	
	Cottonseed	4.3–192.1	
	Spices	0.03–69.2	
	Dried figs	2.0–278.04	
OTA	Barley	0.16–184.24	[6,12,58,59,60]
	Rye	0.05–63	
	Wheat	1.5–823	
	Maize	5.0–44.0	
	Coffee	0.6–4.5	
	Cocoa beans	1.0–277.5	
	Rice	0.15–1164	
	Dried vine fruit	0.06–100.0	
	Spices	0.08–0.52	
	Beer	0.001–2340	
	Wine	0.01–15.6	
ZEA	Maize	$5.7–6.5 \times 10^6$	[6,17••]
	Wheat	1–430	
	Barley	1.25–53	
	Oats	$30–1.31 \times 10^6$	
	Rye	24–199	
	Rice	21.7–1169	
FUM	Maize	0.02–16760	[6,17••]
	Sorghum	0.11–2117	
	Rice	48.2–5200	
T-2	Wheat	3.33–160	[17••,61,62,63]
	Maize	3.33–255	
	Barley	5–547	
	Oats	23–958	
	Rye	4.17–193	
HT-2	Wheat	3.33–46.5	[63]
	Maize	3.33–110	
	Barley	8.33–46.5	
	Oats	10–1150	
	Rye	5–12.5	
DON	Wheat	$0.016–5 \times 10^7$	[6,17••]
	Barley	0.132–619	
	Rye	0.043–595	
	Oats and products	$0.0–5.0 \times 10^6$	
	Maize	$0.256–8.85 \times 10^6$	
	Baby food	0.0–0.047	
NIV	Wheat	0.1–285	[62,63]
	Maize	26–340	
	Oat	56–1860	
	Barley	18–351	
PAT	Apple juice	0.057–1000	[6,64]
	Homogenized pear and apple	0.79–0.85	
	Tomato products	4.05–7.15	
AOH	Fruit juices	0.10–16	[23]
	Cereals	0.75–121	
	Wine	0.04–11	
	Beer	0.23–1.6	
	Tomato products	6.1–41.6	
	Sunflower seeds	16–39	

Table 2 (*Continued*)

Mycotoxin	Food	Range (μg/kg or μg/L)[a]	Reference
AME	Fruit juices	0.03–4.9	[23]
	Cereals	0.49–70.2	
	Wine	0.03–1.45	
	Tomato products	1.2–7.8	
	Sunflower seeds	0.64–21	
TeA	Fruit juices	1.10–250	[23,65]
	Dried figs	25–2345	
	Dry chilli	69.72–222	
	Cereals	2.0–2676	
	Cereal-based infant food	30–1200	
	Fruit-based infant food	25–80	
	Bakery products	75–210	
	Wine	0.31–60	
	Tomato products	3.7–4800	
	Sunflower seeds	350–490	

AF, aflatoxins; AME, alternariol methyl ether; AOH, alternariol; DON, deoxynivalenol; FUM, fumonisins; NIV, nivalenol; OTA, ochratoxin A; PAT, patulin; T-2, toxin; TeA, tenuazonic acid; ZEA, zearalenone.
[a] Range represents minimum and maximum contamination levels reported in different countries for each commodity.

Because of similarities in favourable fungal growth conditions, which consist of high temperatures and humid climate (15–30°C, 0.9–0.995 a_w), FUM often co-occur with aflatoxins, especially in corn [52,18•]. FUM limits for maize range from 200 to 3000 μg/kg in different countries.

Trichothecenes

Trichothecenes are a family of mycotoxins produced by different species of the genus *Fusarium*. They are a complex group of chemically related sesquiterpenoids that share a tricyclic nucleus called trichodiene characterized by a double bond at the 9,10 position and an epoxide group between carbons 12 and 13, responsible for its toxicity.

They do not degrade in normal food processing and are stable at room temperature.

This group of toxins can be divided into four subgroups (A, B, C and D) according to their chemical structure, of which the highest toxicity and frequency of occurrence belong to groups A (T-2 and HT-2 toxins, diacetoxiscirpenol) and B (deoxynivalenol, nivalenol). Trichothecenes of type A and B are the most prevalent contaminants in wheat, barley, oats and maize. As a group, the acute toxicity of trichothecenes A is greater than that of trichothecenes B, but the concentration of trichothecenes B found in contaminated cereals is generally higher than that of trichothecenes A [4••,17••].

Moderate rather than warm temperatures and humid conditions favour the production of type A trichothecenes, while rainy or humid weather coinciding with host flowering and early kernel filling stages favour the production of type B trichothecenes [20]. Levels of trichothecene contamination reported in cereals and by-products are shown in Table 2.

T-2 and HT-2 toxins

F. langsethiae is the main T-2 and HT2 producer, but other species like *F. poae* and *F. sporotrichioides* can also synthesize them. Human intoxication by T-2 and HT-2 is described as Alimentary Toxic Aleukia (ATA) and includes sepsis, hemorrhages, inhibition of hematopoiesis and lymphoid depletion. The same symptoms have been described in domestic animals together with necroses in the upper gastrointestinal tract [17••].

Optimal environmental conditions for production of these toxins by *F. langsethiae* are 0.97–0.997 a_w and 25–28°C [53,54].

Limits in food and food products are in the range 15–1000 μg/kg.

Deoxynivalenol

The fungal species responsible for DON contamination are *F. graminearum*, *F. culmorum*, *F. cerealis* (*F. croockwellense*), *F. sporotrichioides*, *F. poae*, *F. tricinctum*, and *F. acuminatum*. The gastrointestinal system is the target organ of this toxin [21]. Toxic symptoms of DON are food refusal, vomiting, and digestive disorders with losses of weight gain. DON is the most important among the Type B trichothecenes due to its natural occurrence in high levels. Because of its effects in humans along with its resistance to food processing great efforts to control its presence in food have been done [22]. Optimum production of this toxin occurs at 26–30°C and 0.995 a_w [52].

Limits for DON in cereals and by-products range from 200 to 2000 μg/kg.

Nivalenol

NIV is produced by *F. cerealis* (*F. crookwellense*), *F. poae*, *F. nivale*, *F. culmorum*, and *F. graminearum*. NIV toxic effects include bone marrow toxicity, erythropenia, leucopenia, hemorrage, toxicity to lymphoids organs, diarrhea, and damage to the epithelial membranes of the intestine, the thymus and testis.

Nivalenol has often been reported in maize red ear rot throughout the European maize growing areas. It is a typical metabolite after dry and hot summers when harvest is performed earlier than usual [17••].

Regulations for nivalenol have not yet been established but given its relatively higher toxicity, as compared to DON, more attention should be given to this toxin.

Patulin

Penicillium expansum is the fungus that causes blue rot, a post-harvest disease of apples and pears, and to a lesser extent of other fruits. This fungus is primarily responsible for the occurrence of patulin in apples, pears and by-products (Table 2). Special attention is required when apples are destined for infant foods. As the fungus grows even at low temperatures, cold storage of the fruits does not prevent deterioration or toxin accumulation (opt. 16–17°C, 0.99 a_w) [55].

Patulin is a polyketide lactone that is heat-stable, so it is not destroyed by pasteurization or thermal denaturation. It has genotoxic and teratogenic effects and it has shown immunosuppressive activity.

Because of the prevalence and toxicity of patulin, the Codex Alimentarius in addition to the US FDA has set limits of 50 μg/kg for apple products. The European Union has gone further and has imposed a 10 μg/kg limit on baby foods and formulas.

Alternaria toxins

Alternaria is known to produce a wide spectrum of mycotoxins that can contaminate food products. The most relevant ones regarding their health risk are: the tetramic acid derivative, tenuazonic acid (TeA), the dibenzopyrone derivatives, alternariol (AOH), and alternariol methyl ether (AME), and perylene derivatives altertoxins (ATXs). TeA is acutely toxic for chickens and dogs and has been related to a haematological disorder in Africa. AOH and AME have been associated with high levels of oesophageal cancer in China [23]. The altertoxins have shown to be more mutagenic and acutely toxic than AOH and AME [24,25]. Several *Alternaria* species among the group of small-spored *Alternaria* are capable of producing these toxins, especially the ones belonging to *A. alternata*, *A. tenuissima*, and *A. arborescens* species-groups, which are commonly present in a wide variety of foods [26]. *Alternaria* toxins have been found in a large range of commodities of plant origin and their derived products; fruits, vegetables, cereals, dried fruits, fruit juices, wine, beer, bakery products, and infant foods (Table 2) [23].

Environmental conditions favouring toxin biosynthesis differ for each toxin, but most can be produced from refrigeration temperatures to >30°C, with optimum in a range 25–30°C and moderate to high humidity.

There are currently no statutory or guideline limits set for *Alternaria* mycotoxins worldwide, although their relevance in food and feeds is currently under discussion. The European Food Safety Authority published a report on the risks of *Alternaria* toxins for animal and public health, stating that more information is needed on their toxicokinetics, occurrence, and influence of food and feed processing on these mycotoxins to enable their correct risk assessment and establish legislation in food products [27].

Effect of food processing on mycotoxins and decontamination methods

Several efforts are made to reduce mycotoxins both in raw materials and processed food. Current strategies to combat mycotoxins can be divided in pre-harvest treatments to reduce or inhibit production of the toxins in the field, and post-harvest remediation of contaminated commodities [28•]. However, preventive strategies such as good agricultural practices, plant disease management, and adequate storage conditions might limit mycotoxin levels in the food chain but are not always enough to eliminate mycotoxins completely [29•]. This creates a demand for practical and economical new inactivation and detoxification methods [28•,30].

Food processing can impact mycotoxins content previously existent in raw material by several actions, such as physical removal, chemical transformation which can result in metabolites of lower or higher toxicity, release from masked or entrapped forms which may increase bioavailability, enzymatic detoxification, and adsorption to solid surfaces. Reduction of mycotoxin contamination was documented for cleaning; milling; brewing; fermentation; cooking; baking; frying; roasting; flaking; alkaline cooking; nixtamalization (soaking, cooking in an alkaline solution, and hulling of grains); and extrusion [29•]. However, reduction is dependent on the mycotoxin, matrix, and processing conditions; while concentrations of some mycotoxins can be reduced substantially, others, such as DON, are relatively resistant to degradation [31].

Trending in mycotoxin detoxification has evolved from physical and chemical methods to 'natural' or environmental friendly and biological methods. Table 3 summarizes physical, chemical and biological decontamination

Table 3

Detoxification methods for mycotoxins in foods

Method	Mycotoxin	Food commodity	References
Physical methods			
Sorting	Trichothecenes	Cereals	[29]
	AF	Grains	[29]
Sieving	FUM, DON, ZEN	Corn	[29]
Floating	AF	Corn kernels	[32]
	DON, ZEA	Maize, wheat	[29]
Washing (water or alcaline solutions)	DON, ZEA	Barley, corn	[29]
Dehulling	AF	Maize	[29]
Steeping	AF, FUM, OTA, ZEA, DON	Corn	[29]
Milling	DON, ZEA	Wheat	[29]
	AF, FUM, ZEA	Maize	[29]
Roasting	AF	Peanuts, pecans, maize	[29]
	OTA	Coffee beans	[29]
Quick-drying (100–180 °F, 6–48 hours)	AF, OTA, FUM, DON	Coffee cherries	[33]
Extrusion	ZEA, FUM	Maize grits	[29]
UV irradiation	AF	Almonds, cereals, pistachio	[28•,29,30]
	PAT	Apple juice, cider	[34]
	FUM	Maiz, wheat	[30]
Gamma irradiation	AF	Peanuts, pistachios, rice, corn	[29]
Cold plasma	AF	Nuts	[29]
	OTA, FUM	Date palm fruits	[35]
Binders	PAT (activated charcoal)	Cider	[29]
	AFM_1 (bentonite)	Milk	[29]
Chemical methods			
Acid treatment	AF	Maize	[29]
Ammoniation	AF	Maize, peanut meal, cottonseed meal	[29,30]
	OTA	Maize, wheat, barley	[29]
Ozone	AF	Peanuts, paprika, figs	[29,30]
	ZEA, OTA	Corn	[15]
	DON	Corn	[30]
Hydrogen peroxide	AF	Figs, corn, peanut meal, milk	[29]
Reducing agents	AF	Maize, dried figs	[29]
	DON	Maize, wheat	[29,30]
Organic acids	AF	Maize	[30]
	DON	Cereal-based feeds	[36]
Natural methods			
Essential oils	AF	Melon seeds	[10]
	DON	Wheat	[37]
Plant extracts	AOH, AME, TeA	Tomato fruits	[38]
Biological methods			
Bacteria	DON	Corn, wheat	[37,39]
	Trichothecenes	Animal feed	[40]
	AF	Pistachio, corn	[41]
Yeasts	OTA	Grape juice, wine, coffee	[42,43]
	PAT	Apples	[8]
	ZEA	Wheat flour	[44]
Moulds	ZEA	Corn steep liquor	[40]
	AF	Rice	[41]
Genetical engineering	FUM	Maize	[29]

AF, aflatoxins; AFM_1, aflatoxin M_1; AME, alternariol methyl ether; AOH, alternariol; DON, deoxynivalenol; FUM, fumonisins; OTA, ochratoxin A; PAT, patulin; T-2, toxin; TeA, tenuazonic acid; ZEA, zearalenone.

strategies that were able to reduce mycotoxin contamination in food and feeds.

Although a wide range of remediation strategies have been investigated and several detoxification approaches can be found in the literature, many of these treatments have proven to be too expensive, efficient only at small-scale, and unsuitable for real-world application. The increasing public concern on the potential risk of fungicides and harmful chemicals in foods have encouraged the development of new methods based on innocuous and inherent constitutes in agricultural products. The

screening for microorganisms able to biotransform certain mycotoxins has been a popular strategy in the last decade, as well as direct application of bioactive materials, such as enzymes, either commercially available or synthesized by these microorganisms [28•]. However, most of these natural methods have only proved effective at laboratory scale, or in *in vitro* experiments, and their efficacy in the food chain remains to be tested. Additionally, many of them have not yet been approved for their use in human food commodities. Their main drawbacks are that microbial performance is doubtful when multiple mycotoxin degradation is required, and some microorganisms might convert the toxins to metabolites of equal or higher toxicity [45].

It is worth mentioning, however, those methods which have been recently patented, since they present a higher probability to be commercialized in the near future. Several *Bacillus* spp. strains have shown 100% bio-transformation of DON and ZEA [39,46,47]. Other bacteria and yeast genera have been 100% effective at reducing OTA, ZEA and FB_1 (*e.g. Trichosporon*, *Rhodotorula*, *Sphingomonas*, *Stenotrophomonas*, *Alcaligenaceae*, *Pichia*) [48,49]. These biocontrol microorganisms usually originate from the soil where the crop is grown or the gastrointestinal system of animals in contact with the mycotoxin [28•].

The replacement of microorganisms by their enzymes as detoxification tools is a more recent trend. Enzymes are very attractive targets to biodegrade mycotoxins, due to their higher safety, specificity, and ease-of-handling in comparison to microorganisms. Recent developments of recombinant DNA technologies, activity-based screening and protein engineering, have encouraged the search for novel enzymes involved in mycotoxin bio-transformation [28•]. In recent studies, enzymes degrading PAT, FUM, and OTA into less toxic metabolites have been found in many species of bacteria and yeast [50,51]. Bacterial enzymes have been used in animal feeds to detoxify FUM, and their application in food production is considered in the pertaining patent. Genetically engineered maize varieties able to detoxify FUM by enzymes from a yeast were developed [29•].

Enzymatic detoxification appears conceivable for any mycotoxin but its potential for real-world application still needs to be evaluated. Their impact on the food chain should be thoroughly assessed, and the enzymes involved must be compatible with current industrial food processes. Even though this alternative seems promising, no enzyme has so far been authorized in the EU for the reduction of mycotoxin contamination in food. Future perspectives in this field involve enzyme engineering techniques to enhance activity or alter specificity and stability, aided by computational screening methods to study protein-toxin interactions *in silico*, and bioavailability and toxicity studies of transformation products by an effective systematic approach [28•,29•].

Conclusions

Exposure to mycotoxins occurs worldwide, although their prevalence and quantities in food may vary due to geographic and climatic differences. Economic losses resulting from mycotoxin-contaminated crops can be derived from reduced crop yields, lower animal performance and increased disease incidence. Impact on human populations includes endemic diseases, high cancer incidence, morbidity, and premature death. Costs associated with mycotoxin contamination are huge and have been underestimated in the past. Despite efforts to find effective methods of reducing mycotoxins, they will not have the intended benefits unless they are adopted by the populations at highest risk of mycotoxin exposure. The development of mitigation strategies should prioritize low cost technologies, of easy application even in developing regions, and effective at industrial levels in food processing. These methods should focus on the mycotoxins with highest incidence and toxicity.

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