Food Research International xxx (xxxx) xxx

Contents lists available at ScienceDirect

Food Research International

journal homepage: www.elsevier.com/locate/foodres

Novel strategies for degradation of aflatoxins in food and feed: A review

Yongpeng Guo, Lihong Zhao *, Qiugang Ma, Cheng Ji

State Key Laboratory of Animal Nutrition, College of Animal Science and Technology, China Agricultural University, Beijing 100193, PR China

ARTICLE INFO

Keywords:
Mycotoxins
Irradiation
Cold plasma
Ozone
Organic acids
Nanozyme

ABSTRACT

Aflatoxins are toxic secondary metabolites mainly produced by *Aspergillus* fungi, posing high carcinogenic potency in humans and animals. Dietary exposure to aflatoxins is a global problem in both developed and developing countries especially where there is poor regulation of their levels in food and feed. Thus, academics have been striving over the decades to develop effective strategies for degrading aflatoxins in food and feed. These strategies are technologically diverse and based on physical, chemical, or biological principles. This review summarizes the recent progress on novel aflatoxin degradation strategies including irradiation, cold plasma, ozone, electrolyzed oxidizing water, organic acids, natural plant extracts, microorganisms and enzymes. A clear understanding of the detoxification efficiency, mechanism of action, degradation products, application potential and current limitations of these methods is presented. In addition, the development and future perspective of nanozymes in aflatoxins degradation are introduced.

1. Introduction

Aflatoxins (AFs) are a class of carcinogenic mycotoxins produced by the *Aspergillus* species, notably *Aspergillus flavus* and *A. parasiticus*, and are commonly found in staple food crops such as corn, rice, peanuts, dried fruits and spices as well as milk products (Ismail et al., 2018; Reddy et al., 2010; Rushing & Selim, 2019). They were first discovered in the early 1960s as the principal etiological agents of"Turkey X disease" resulting in the deaths of over 100,000 turkeys in England (Blount, 1961). Both *A. flavus* and *A. parasiticus* produce aflatoxin B_1 (AFB_1) and aflatoxin B_2 (AFB_2); *A. parasiticus* also produces aflatoxin G_1 (AFG_1) and aflatoxin G_2 (AFG_2). Among the four toxins, AFB_1 is the most harmful and is responsible for more than 75% of all aflatoxins related food and feed contamination (My & Sachan, 1997). In the liver, AFB_1 undergoes cytochrome P450-mediated metabolism, including the epoxidation to AFB_1-exo-8, 9-epoxide and AFB_1-endo-8, 9-epoxide, hydroxylation to aflatoxin M_1 (AFM_1) and aflatoxin Q_1 (AFQ_1), and demethylation to aflatoxin P_1 (AFP_1) (Bbosa, Kitya, Odda & Ogwal-Okeng, 2013). AFB_1-exo-8, 9-epoxide covalently binds to DNA, proteins and phospholipids to form adducts, resulting in genetic, metabolic, signaling and cell structure disruptions (Benkerroum, 2020). The wide range of toxic effects caused by aflatoxin exposure is named aflatoxicosis and has been described in two forms: (i) "acute intoxication" caused by short exposure to high amount of aflatoxins and characterized by serious liver damage, jaundice, haemorrhage, oedema and eventually death; (ii) "chronic sublethal exposure," which leads to immunosuppression, nutritional disorders and cancer (Marchese et al., 2018).

The International Agency for Research on Cancer (IARC) has classified AFB_1 as a Group I human carcinogen (Ostry, Malir, Toman, & Grosse, 2017). Globally more than 5 billion people are chronically exposed to AFB_1 (Pandey et al., 2019). The annual global burden of AFB_1-induced human hepatocellular carcinoma (HCC) is as high as 155,000 cases, with most occurring in Sub-Saharan Africa and Southeast Asia (Liu & Wu, 2010). In China, liver cancer is the second most prevalent cancer, accounting for 19.33% of all kinds of cancers (Chen & Zhang, 2011). Prospective cohort studies have revealed that the major causative factors associated with primary liver cancer in endemic area of China are chronic infection with hepatitis B virus (HBV) and extended exposure to high levels of aflatoxins in the diet (Chen et al., 2013). While AFB_1 is likely to be only a minor risk factor for HCC development in Europe, chronic exposure to AFB_1 may nevertheless impair immune system and child growth (EFSA, 2007). Considering the potential damage of dietary aflatoxins to the consumer health, many countries and regions have imposed maximum limits for aflatoxins in food and feed. The U.S. Food and Drug Administration (FDA) has specified the maximum acceptable limit of 20 $\mu g\ kg^{-1}$ for total AFs in all food except milk (FDA, 2011). In the European Community (EC), even more stringent regulations have been established, with the maximum permissible levels of 2 and 4 $\mu g\ kg^{-1}$ for AFB_1 and total AFs, respectively, in peanuts, dried fruits and cereals for direct human consumption or as ingredients

* Corresponding author.
E-mail addresses: 18771951786@163.com (Y. Guo), zhaolihongcau@cau.edu.cn (L. Zhao), maqiugang@cau.edu.cn (Q. Ma), jicheng@cau.edu.cn (C. Ji).

https://doi.org/10.1016/j.foodres.2020.109878
Received 7 June 2020; Received in revised form 31 October 2020; Accepted 1 November 2020
Available online 21 November 2020

in food (EC, 2010). In China, the legal limits for AFB_1 in cereal products intended for human consumption range from 5 to 10 μg kg^{-1} whereas levels in animal feedstuffs are allowed to be much higher, reaching upwards from 20 to 50 μg kg^{-1} (Ma et al., 2018).

Current strategies to reduce the risk of consumer exposure to aflatoxins can be divided into pre-harvest prevention of aflatoxins production and post-harvest aflatoxins elimination. The application of Good Manufacturing Practices (GAPs), i.e., the use of fertilizers, pest control and fungal-resistant crop varieties, harvesting at the right time and maintaining low moisture content and temperature during storage can inhibit mold growth and aflatoxins production in grains. However, these prevention strategies are not always effective to achieve aflatoxin-free food and feed. This emphasizes the need of post-harvest intervention to eliminate aflatoxin contamination. Conventional food processing methods like sorting, cleaning, dehulling and milling can only remove highly contaminated fractions from bulk materials (Karlovsky et al., 2016). The decomposition temperatures of aflatoxins range from 237 to 306 °C (Rustom, 1997). Thus, aflatoxins are quite resistant to ordinary cooking, frying, baking and roasting (Kabak, 2009). The use of aflatoxin binders for the prevention of aflatoxicosis has become popular in animal nutrition. Several reports documented that mineral adsorbents like bentonite, zeolite, montmorillonite and aluminosilicate could partly or fully counteract the toxic effects of dietary aflatoxins in farm animals (Jard, Liboz, Mathieu, Guyonvarc'h, & Lebrihi, 2011; Vekiru et al., 2015). However, these mineral adsorbents may also bind vitamins, minerals and amino acids. Furthermore they may induce cytotoxic effects such as oxidative stress, reduction in cell viability, apoptosis, and DNA damage (Elliott, Connolly, & Kolawole, 2019). Organic adsorbents based on yeast and bacterial cell wall have also been used to bind aflatoxins but further studies are needed to improve their binding specificity for aflatoxins (Luo, Liu, Yuan, & Li, 2020). As aflatoxicosis continues to be a problem in humans and animals, several novel strategies have been developed and optimized over the past decade that show promise in degrading aflatoxins in food and feed. These strategies can be broadly categorized as physical, chemical and biological (Umesha et al., 2017; Udomkun et al., 2017). Physical approaches based on advanced oxidation technology such as irradiation and cold plasma allow for rapid degradation of aflatoxins (Calado, Venâncio, & Abrunhosa, 2014; Gavahian & Cullen, 2019). Chemical means involve the use of ozone, electrolyzed oxidizing water, organic acids and natural plant extracts, which are widely accepted as safe food additives in many countries like China and the USA (Diao, Hou, & Dong, 2013; Rahman, Khan, & Oh, 2016; Lee, Her, & Lee, 2015; Loi, Paciolla, Logrieco, & Mulè, 2020). Biological methods take the form of microbial and enzymatic transformation of aflatoxins into non-toxic or less toxic metabolites (Ji, Fan, & Zhao, 2016; Kumar, Mahato, Kamle, Mohanta, & Kang, 2016). In this paper, our aim is to provide an updated and comprehensive review of these novel aflatoxin degradation technologies. Moreover, we will provide a brief description about recent development of nanozymes in aflatoxins degradation.

2. Physical degradation of aflatoxins

2.1. Degradation of aflatoxins by irradiation

In general irradiation can be classified into two forms: ionizing (e.g. X-rays, ultraviolet rays, gamma rays, and electron beam) and non-ionizing irradiation (e.g. radio waves, microwaves, infrared waves, and visible light waves). Extensive research has been performed to apply irradiation technology for eliminating mycotoxins. Table 1 presents the outcomes from recent studies on aflatoxin degradation in food and feed by irradiation.

2.1.1. Degradation of aflatoxins by gamma irradiation

Gamma rays are electromagnetic radiation emitted from the decay of an unstable source such as a radioactive isotope (e.g., ^{60}Co, ^{192}Ir, ^{139}Cs,

Table 1
Summary of recent studies (2010 to date) on aflatoxins degradation in food and feed with irradiation.

Treated sample	Treatment parameters	Aflatoxin (μg kg^{-1} or μg L^{-1})	Degradation (%)	Reference
^{60}Co gamma				
Corn	10 kGy	AFB_1 (57–1210)	85.6–98.6	(Markov et al., 2015)
Corn	8 kGy	AFB_1 (50.4)	60.3	(Mohamed, El-Dine, Kotb, & Saber, 2015)
Wheat	8 kGy	AFB_1 (37.6)	69.3	
Rice	8 kGy	AFB_1 (27.5)	64.7	
Peanut	9 kGy	AFB_1 (300)	43	(Patil, Shah, Hajare, Gautam, & Kumar, 2019)
Brazil nut	10 kGy	AFB_1 (4.8)	84.2	(Assuncao, Reis, Baquiao, & Correa, 2015)
Red chilli	6 kGy	AFB_1 (11–35)	86–98	(Iqbal et al., 2013)
Dried hot pepper	6 kGy	AFT (1.1)	6	(Iqbal, Amjad, Asi, & Arino, 2012)
White pepper	30 kGy	AFB_1 (60), AFB_2 (18), AFG_1 (60) and AFG_2 (18)	50.6, 35.2, 47.7 and 42.9	(Jalili, Jinap, & Noranizan, 2012)
Black pepper	30 kGy	AFB_1 (60), AFB_2 (18), AFG_1 (60) and AFG_2 (18)	47.2, 39.4, 47.4 and 40.4	
Almond	15 kGy	AFB_1 (20), AFB_2 (20), AFG_1 (20) and AFG_2 (20)	19.3, 11.0, 21.1and 16.6	(Vita, Rosa, & Giuseppe, 2014)
Cattle feed	10 kGy	AFB_1 (50)	85	(Markov et al., 2015)
Poultry feed	15 kGy	AFB_1 (25), AFB_2 (25), AFG_1 (25) and AFG_2 (25)	18.2, 11.0, 21.1 and 13.6	(Di Stefano, Pitonzo, Cicero, & D'Oca, 2014)
Electron beam				
Peanut	300 kGy	AFB_1 (1000)	70	(Liu et al., 2018)
Brazil nut	10 kGy	AFB_1 (4.8)	65.7	(Assuncao, Reis, Baquiao, & Correa, 2015)
Ultraviolet				
Wheat	254 nm at 0.1mW cm^{-2} for 160 min	AFT (13–23)	65–90	(Ghanghro, Nizamani, Channa, Ghanghro, & Sheikh, 2016)
Red chilli powder	365 nm for 60 min	AFB_1 (1872)	87.8	(Tripathi & Mishra, 2010)
Peanut	254 nm for 10 h	AFB_1 (350)	99.1	(Garg, Aggarwal, Javed, &

(continued on next page)

Table 1 (*continued*)

Treated sample	Treatment parameters	Aflatoxin (μg kg $^{-1}$or μg L^{-1})	Degradation (%)	Reference
				Khandal, 2013)
Peanut	220–400 nm at 0.8 mW cm^{-2} for 80 min	AFB_1 (2000)	100	(Chang, Jin, Liu, Liu, & Wang, 2013)
Peanut oil	220–400 nm at 0.8 mW cm^{-2} for 30 min	AFB_1 (2000)	100	(Liu et al., 2011)
Peanut oil	365 nm at 6.4 mW cm^{-2} for 10 min	AFB_1 (52.0)	86.1	(Diao et al., 2015b)
Peanut oil	365 nm at 55–60 mW cm^{-2} for 20 min	AFB_1 (128)	96	(Mao et al., 2016)
Peanut oil	254 nm for 120 min	AFB_1 (83)	35.1	(Xu, Ye, Cui, Song, & Xie, 2019)
Photocatalysis				
Peanut oil	TiO_2 layer in a closed-loop reactor; 254 nm for 120 min	AFB_1 (83)	60.4	(Xu, Ye, Cui, Song, & Xie, 2019)
Peanut oil	Immobilized TiO_2; UV of 92 mW cm^{-2} and visible of 200 mW cm^{-2} for 4 min	AFB_1 (674.3) and AFB_2 (311.6)	100	(Magzoub et al., 2019)
Pulsed light				
Rough rice	0.52 J cm^{-1} per pulse for 80 s	AFB_1 (132) and AFB_2 (45)	75.0 and 39.2	(Wang et al., 2016)
Rice bran	0.52 J cm^{-1} per pulse for 15 s	AFB_1 (36) and AFB_2 (4.4)	90.3 and 86.7	
Peanut oil	0.4 J cm^{-1} per pulse for 800 s	AFT (40)	78	(Abuagela, Iqdiam, Baker, & MacIntosh, 2018)
Microwave				
Alkalized corn	1650 W for 5.5 min	AFB_1 (22.5) and AFB_2 (69.6)	36 and 58	(Pérez-Flores, Moreno-Martínez, & Méndez-Albores, 2011)
Corn flour	Heating in microwave oven for 10 min	AFB_1 (100)	67.7	(Alkadi & Altal, 2019)
Peanut	480 W for 5 min	AFB_1 (300)	67	(Patil, Shah, Hajare, Gautam, & Kumar, 2019)
Peanut	Heating in microwave oven at 92 °C for 5 min	AFB_1 (5–183) and AFB_2 (7–46.7)	50–60 and 100	(Mobeen, Aftab, Asif, & Zuzzer, 2011)

AFB_1, Aflatoxin B_1; AFB_2, Aflatoxin B_2; AFG_1, Aflatoxin G_1; AFG_2, Aflatoxin G_2; AFT, Total aflatoxins, the sum of AFB_1, AFB_2, AFG_1 and AFG_2.

and ^{70}Tm). Gamma rays are the preferred source of irradiation for food processing because of their high reactivity and penetrability. The irradiation of food up to an overall dose of 10 kGy causes no toxicological hazards and no special microbiological or nutritional problems (WHO, 1999). Gamma irradiation can facilitate radiolysis of water and generation of highly reactive free radicals like radical hydrogen ($H^{\bullet}$), superoxide radical ($O_2^{\bullet-}$) and hydroxyl ion (OH^-), which play an important role in the destruction of aflatoxins (Rustom, 1997). A study conducted by Wang et al. (2011) examined the structure of AFB_1 radiolytic products. This analysis revealed that the double bond of the terminal furan ring was no longer in existence in most of radiolytic products due to free-radical addition reaction during gamma irradiation. The double bond in the terminal furan ring of AFB_1 is known to be associated with its toxicity. In the liver, the oxidation of the double bond in the terminal furan ring of AFB_1 by hepatic cytochrome P450 enzymes (CYPs) yields AFB_1-exo-8, 9-epoxide, which can react with the N^7 atom of guanine to generate pro-mutagenic DNA adducts (Bbosa, Kitya, Odda & Ogwal-Okeng, 2013). Thus, the loss of the double bond of the terminal furan ring in AFB_1 after gamma irradiation treatment led to a significant reduction of its cytotoxicity in Pk15, HepG2 and SH-SY5Y cells (Domijan et al., 2019).

The efficiency of gamma irradiation-assisted degradation of aflatoxins depends on many factors, such as radiation dose, mycotoxin concentration, water content and matrix composition. Most of the studies in the literature concluded that gamma irradiation at levels ranging from 5 to 10 kGy could eliminate a significant amount of aflatoxins in food products (Table 1). Iqbal et al. (2013) studied the efficiency of aflatoxins degradation in red chillies through gamma irradiation and observed that the application of 6 kGy reduced the level of AFB_1 by more than 86%. Similarly, Markov et al. (2015) reported that the treatment of corn with gamma ray at 5 kGy resulted in a 69.8% reduction of AFB_1 level, while the dose of 10 kGy detoxified AFB_1 by 94.5%. The experiments performed by Assuncao, Reis, Baquiao, and Correa (2015) also showed that gamma irradiation at 5 to 10 kGy was sufficient to eliminate 70.6 to 84.2% of AFB_1 in Brazil nuts. Other studies nevertheless showed that gamma irradiation is not very effective in aflatoxins degradation. Jalili, Jinap, and Noranizan (2012) reported that gamma irradiation at a dose of 10 kGy did not significantly affect the aflatoxins content in black and white pepper. In addition, Di Stefano, Pitonzo, Cicero, and D'Oca (2014) conducted gamma irradiation study with poultry feed and obtained only 18.2, 11.0, 21.1 and 13.6% reduction of AFB_1, AFB_2, AFG_1 and AFG_2, respectively, with a dose of 15 kGy. Gamma irradiation also presents high microbial inactivation capacity, thus allowing the reduction of microbial load and extension of food shelf life. The interest in the adoption of gamma irradiation in food decontamination is increasing as consumers are beginning to appreciate the benefits of irradiated food. Up to now, more than 55 countries including China, USA, Japan and European countries have approved this technology in food processing under certain conditions (Priyadarshini, Rajauria, O'Donnell, & Tiwari, 2019). However, gamma irradiation seems to be not suitable for food with high lipid and vitamin content, mainly due to the extensive peroxidation of unsaturated bonds in the polyunsaturated fatty acids, resulting in the increase of the onset of oxidative rancidity in food (Caulfield, Cassidy, & Kelly, 2008).

2.1.2. *Degradation of aflatoxins by electron beam irradiation*

Electron beam (EB) irradiation has also shown potential for degrading aflatoxins, and this technology has the advantages of short processing time, low equipment costs, and dosage control. EB irradiation of AFB_1 in an acetonitrile solution resulted in the formation of two degradation products, $C_{14}H_{12}O_5$ and $C_{17}H_{14}O_5$ (Wang et al., 2015a). In an aqueous solution, the reduction of AFB_1 by EB irradiation led to the generation of five by-products, with a loss of the double bond in the terminal furan ring in four of the five products (Liu et al., 2016). Preliminary safety assessments of the degradation products conducted with the Ames test and 3-(4,5-Dimethylthiazol-2-yl)-2,5-

diphenyltetrazolium bromide (MTT) viability assay, showed that the mutagenicity and cytotoxicity of EB-irradiated AFB_1 were significantly decreased. Nevertheless, the decontamination efficiency of EB irradiation is less than that of gamma irradiation. Gamma irradiation at doses of 5 and 10 kGy reduced AFB_1 content in Brazil nuts by 70.6 and 84.2%, respectively, whereas EB irradiation at the same doses resulted in AFB_1 reduction by 53.3 and 65.7%, respectively (Assuncao, Reis, Baquiao, & Correa, 2015). Additionally, Liu et al. (2018) found that EB irradiation was not very effective in degrading AFB_1 in peanut meal, since an irradiation dose of 300 kGy, which was ten times of the maximum allowable dosage permitted by FDA, was required for achieving a 70% reduction of AFB_1.

2.1.3. Degradation of aflatoxins by ultraviolet irradiation

Ultraviolet (UV) irradiation has been known for decades as an effective physical method for the destruction of aflatoxins due to their photosensitivity. As a non-thermal food decontamination technology, UV irradiation offers the advantages of being practical and cost effective, and eco-friendly as it exhibits no toxic effects and no waste generation (Gayán, Condón, & Álvarez, 2014). AFB_1 absorbs UV rays at 222, 265 and 362 nm, with the absorption maxima at 362 nm (Samarajeewa, Sen, Cohen, & Wei, 1990). The formation of hydroxyl free radicals ($OH^{\bullet}$) initiated by UV irradiation could attack the terminal double bond at the C8-C9 position of AFB_1 (Liu et al., 2010), and the photodegradation pathway of AFB_1 in water under UV irradiation was depicted in Fig. 1. The results of the Ames test and cell viability assay indicated that the mutagenicity and cytotoxicity of the photodegradation products were much lower than that of AFB_1 (Diao et al., 2015b; Mao et al., 2016). UV intensity and irradiation duration are key factors affecting aflatoxins elimination efficiency. UV irradiation at 800 μw cm^{-2} for 30 min was sufficient to completely remove AFB_1 in peanut oil, whereas the toxin was reduced by about 79 and 85% at the intensity of 200 and 400 μw cm^{-2}, respectively (Liu et al., 2011). The treatment of peanuts with UV light at 254 nm was found to reduce AFB_1 level by 59.7% within 2 h, and by up to 99.1% after 10 h (Garg, Aggarwal, Javed, & Khandal, 2013). Moreover, Ghanghro, Nizamani, Channa, Ghanghro, and Sheikh (2016) showed that more than 80% of aflatoxins in wheat samples were eliminated when exposed to UV short wave at 254 nm for 160 min. In general, the application of moderate doses of UV irradiation does not cause extensive adverse effects on the physicochemical and sensory characteristics of food products (Delorme et al., 2020). UV light can easily penetrate through clear or transparent liquids. Nevertheless, its penetration capacity into solid materials is limited, which results in low decontamination efficiency in food products with high content of suspended solids (Fan, Huang, & Chen, 2017). Thus, opaque or granular food products need to be presented as a thin layer during UV irradiation detoxification (Diao et al., 2015a).

2.1.4. Degradation of aflatoxins by photocatalysis

Several recent studies have demonstrated that the use of UV–visible irradiation in combination with semiconducting photocatalysts can increases the efficiency of aflatoxins degradation in liquid matrix (Sun, Zhao, Xie, & Liu, 2019; Xu, Ye, Cui, Song, & Xie, 2019). During the photocatalytic degradation process, the photo-generated valence band holes (h^{+}), hydroxyl free radicals ($OH^{\bullet}$) and superoxide radical ($O_2^{\bullet-}$) are capable of directly oxidizing AFB_1 (Sun, Zhao, Xie, & Liu, 2019; Mao et al., 2018). The most widely used photocatalyst is TiO_2, as it is highly active under UV irradiation, non-toxic, highly efficient, and has long-term photostability. Sun, Zhao, Xie, and Liu (2019) evaluated photocatalytic degradation of AFB_1 in methanol by activated carbon supported TiO_2 catalyst (AC/TiO_2) under UV–Vis light. The degradation rate reached 95% within 120 min by UV–Vis irradiation in the presence

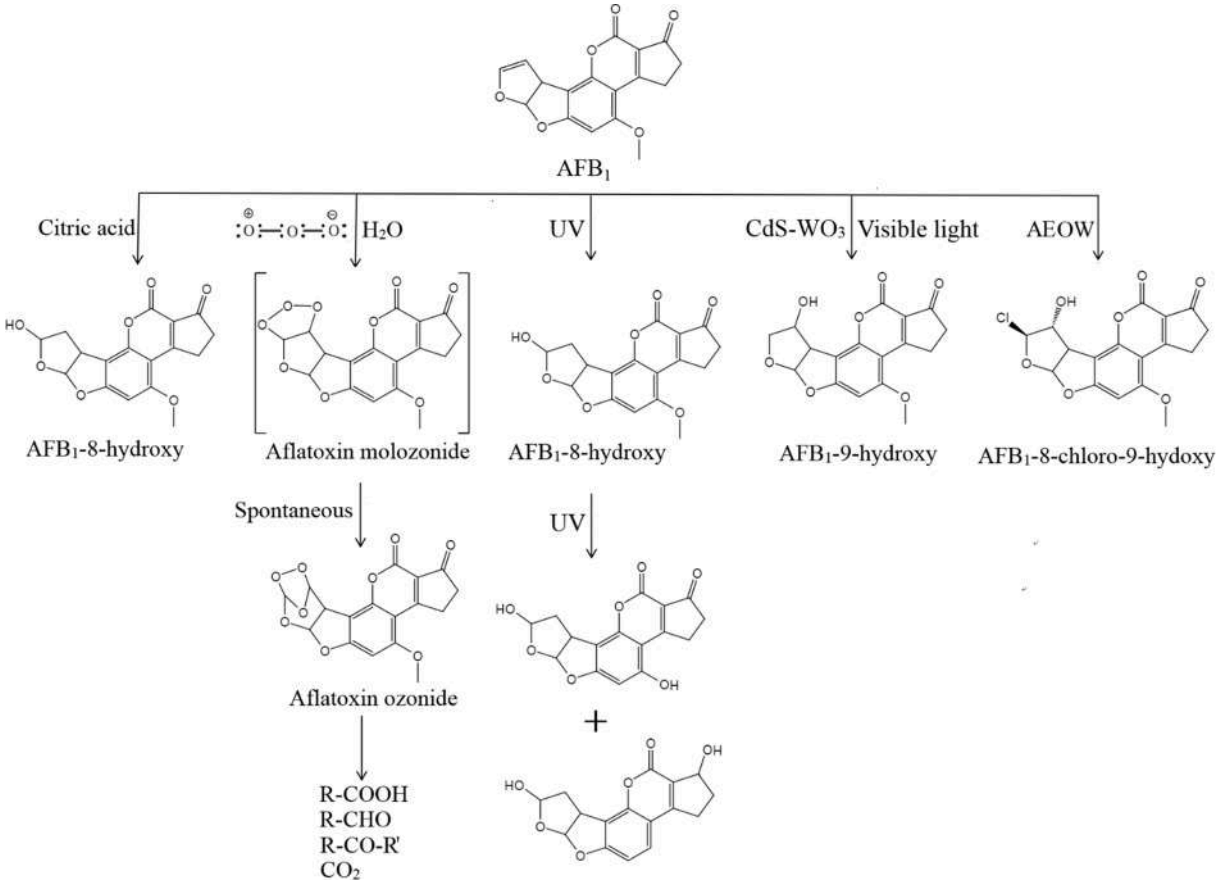

Fig. 1. The degradation pathways of AFB_1 by several physical and chemical treatments.

of AC/TiO_2 (6 mg mL^{-1}), whereas only 50% of AFB_1 was degraded by UV–Vis irradiation alone. Xu et al. (2019) designed an immobilized-bed photocatalytic reactor consisting of a glass tube coated with TiO_2 for the detoxification of AFB_1 in contaminated peanut oil. Approximately 60.4% removal of AFB_1 was achieved within 120 min by employing this TiO_2/UV system, which was higher than that of UV photolysis alone (35.1%). In a study of Magzoub et al. (2019), AFB_1 and AFB_2 in Sudanese peanut oil were almost completely removed by immobilized TiO_2 within 4 min using UV–Vis light. Additionally, the physicochemical characteristics of peanut oil, including fatty acids composition, free fatty acids content, peroxide value, saponification value, acid value, iodine value, moisture and volatile matters as well as the refractive index did not significantly change during the photocatalytic treatment.

The major disadvantage of TiO_2 photocatalyst is its restriction to UV irradiation, which accounts for only 4% of the sunlight spectrum. Thus, efforts have been devoted to developing visible-light-driven photocatalysts for aflatoxins reduction. Jamil, Abbas, Nasr, El-Kady, and Ibrahim (2017) successfully synthesized Sc-doped $SrTi_{0.7}Fe_{0.3}O_3$ nanoparticles and studied their performance as a photocatalyst in the degradation of AFB_1. The results showed that AFB_1 could be completely degraded into carbon dioxide and water by 10 mol% Sc-doped $SrTi_{0.7}Fe_{0.3}O_3$ under visible light with a detoxification rate of 88.2% within 120 min. Mao et al. (2018) reported that nanosized graphitic carbon nitride (g-C_3N_4) sheets exhibited a significantly enhanced photocatalytic activity for the degradation of AFB_1 compared with bulk g-C_3N_4 under visible light irradiation. This is due to better photogenerated charge separation and a larger surface area of nanosized g-C_3N_4 sheets. After treatment for 120 min, the AFB_1 removal efficiency using nanosized g-C_3N_4 sheets reached 70.2%, while it was only 30.8% for bulk g-C_3N_4. In another study of Mao et al. (2019), Clew-like WO_3 decorated with CdS nanoparticles showed superior activity for attacking the C9 site of the double bond in the terminal furan ring of AFB_1 under visible light irradiation, resulting in the formation of AFB_1-9-hydroxy as the major photodegradation product (Fig. 1). Indeed, photocatalysis is a promising technology in AFB_1 degradation, but very little information exists on the stability and safety of photocatalysts.

2.1.5. Degradation of aflatoxins by pulsed light

Another non-thermal technology called pulsed light (PL) has also been employed for the decontamination of aflatoxins in food and feed. Pulsed light is an FDA-approved technology for the rapid and efficient surface decontamination of food products with an upper limit fluence of 12 J cm^{-2} (FDA, 1996). This novel technology creates short, high-intensity flashes of broadband emission light (100–1100 nm) including ultraviolet, visible and infrared rays (Oms-Oliu, Martín-Belloso, & Soliva-Fortuny, 2010). The intensity of the emitted light is about 20, 000 times more intense than direct sunlight at sea-level (Dunn, Ott, & Clark, 1995). Moreau et al. (2013) reported that eight flashes of PL (light flux of 1 J cm^{-2} during one 300 ms flash) degraded 92.7% of AFB_1 in water. Wang et al. (2016) treated rough rice and rice bran with PL at 0.52 J cm^{-1} per pulse. PL treatment of rough rice for 80 s reduced AFB_1 and AFB_2 by 75.0 and 39.2% respectively, while a treatment time of 15 s reduced AFB_1 and AFB_2 in rice bran by 90.3 and 86.7% respectively. Using a brine shrimp lethality assay and the Ames fluctuation assay, Wang et al. (2016) further demonstrated that PL treatment inactivated the cytotoxicity and mutagenicity of AFB_1 and AFB_2. Similarly, Abuagela et al. (2018) observed a 91% reduction in aflatoxins in dehulled peanuts after PL treatment (0.4 J cm^{-1} per pulse). Additionally, it was shown that PL treatment did not significantly affect the chemical qualities such as peroxide value, fatty acid content and acidity value of oil extracted from peanuts, although slight changes in peanut kernel color were noted. However, despite the progress mentioned above, the breakdown products of aflatoxins after PL treatment are still under investigation. Characterization of the possible photodegradation pathways of aflatoxins under PL treatment will provide deep insight into the degradation mechanism and kinetics of this technology. There is also a need for designing cost-effective PL equipment capable of generating high UV output in order to apply this emerging technology at an industrial scale.

2.1.6. Degradation of aflatoxins by microwave heating

Microwaves are electromagnetic waves in frequencies ranging from 300 MHz to 300 GHz with wavelengths from 1 m to 1 mm. The frequency of a domestic microwave is 2450 MHz, while industrial microwave systems generally use either 915 or 2450 MHz. Microwave heating is a unique volumetric heating method, which transforms electromagnetic field energy into thermal energy through the polarization effect of the electromagnetic radiation (Soni, Smith, Thompson, & Brightwell, 2020). Microwaving has been widely applied in the drying, heating, cooking and extraction of food. Some reports also documented the use of microwave heating in degrading aflatoxins in food materials. Pérez-Flores, Moreno-Martínez, and Méndez-Albores (2011) evaluated the effect of microwave treatment during alkaline-cooking of aflatoxin-contaminated corn. The results showed that AFB_1 and AFB_2 were reduced by 36 and 58%, respectively, when the contaminated corn was microwave-heated at a power output of 1650 W for 5.5 min. Moreover, microwave cooking of peanut and peanut products, respectively, resulted in a 50 to 60% reduction of the level of AFB_1, while AFB_2 content decreased to non-detectable limits (Mobeen, Aftab, Asif, & Zuzzer, 2011). Alkadi and Altal (2019) also recently documented the degradation of AFB_1 up to 67.7% in corn flour heated in a microwave oven for 10 min. Overall, microwave heating demonstrated moderate success in reducing aflatoxins levels in food commodities. Microwave manufacturers are able to customize equipment to specific applications and food product types. However, it has always remained a challenge to address the non-uniform temperature distribution during microwave heating, which may lead to the formation of cold and hot spots in the treated food (Menon, Stojceska, & Tassou, 2020). Aflatoxins in cold spots can not be effectively detoxified, while overheating in hot spots may cause nutritional losses and quality deterioration. More studies are also required to optimize the process parameters to increase the degradation efficiency along with structure elucidation and safety evaluation of the degradation products.

2.2. Degradation of aflatoxins by cold plasma

Plasma is a highly energized ionized gas, generally known as the fourth state of matter, consisting of electrons, ions, UV irradiation and reactive neutral species such as reactive oxygen species (ROS) and reactive nitrogen species (RNS) (Kogelschatz, 2004). In general, plasma can be loosely categorized according to its temperature into thermal and cold (also refered to as non-thermal) plasma. The generation of cold plasma can be achieved by means of electrical discharges in gases at atmospheric pressure and a temperature range from 30 to 60 °C (Hertwig, Meneses, & Mathys, 2018). Moreover, cold plasma can be described by the system used to generate it, for example, corona discharge (CD), dielectric barrier discharge (DBD), atmospheric pressure plasma jets (APPJ), and radio frequency plasma (RFP) (Fridman, Chirokov, & Gutsol, 2005).

This rather new technology has been shown to enable the rapid detoxification of aflatoxins at ambient temperature and pressure conditions (Gavahian & Cullen, 2019; Misra, Yadav, Roopesh, & Jo, 2019). Siciliano et al. (2016) used DBD N_2-plasma to degrade aflatoxins inoculated on dehulled hazelnuts. The results showed that approximately 70% of AFB_1 and total aflatoxins were detoxified following 12 min exposure to a 1150 W plasma treatment. Moreover, the authors demonstrated that AFB_1 and AFG_1 were more sensitive to N_2-plasma treatment compared to AFB_2 and AFG_2, respectively. Another study using N_2-plasma found that the performance of plasma in degrading AFB_1 was connected to processing time and plasma frequency (Sakudo, Toyokawa, Misawa, & Imanishi, 2017). According to the results, 15 min of N_2-plasma treatment at 1.5 kpps reduced AFB_1 by more than 90% and

abolished its toxicity to HepG2 cells. Shi, Ileleji, Stroshine, Keener, and Jensen (2017) investigated the effects of carrier gas type (air and modified atmosphere gas containing 65% O_2, 30% CO_2, and 5% N_2) and relative humidity (RH of 5, 40 and 80%) on AFB_1 degradation induced by high voltage atmospheric cold plasma (HVACP). The best result was observed while operating the plasma in a 40% RH modified atmosphere gas wherein 88.3% of AFB_1 in corn was eliminated within 5 min. In the case of peanut samples, 5 min of agitated APPJ treatment decreased total aflatoxins levels by 38% without negatively affecting chemical qualities of peanut oil (Iqdiam et al., 2019). Puligundla, Lee, and Mok (2019) evaluated the effect of corona discharge plasma jet (CDPJ) treatment on the degradation of AFB_1 on glass slides and in spiked food samples. Following CDPJ treatment for 30 min, the AFB_1 concentration on slides was decreased by 95%, whereas AFB_1 levels in rice and wheat were only reduced by 56.6 and 45.7%, respectively. The authors suggested that this disparity could be due to chemical interaction of AFB_1 with the food matrix resisting the degradation of the toxin. In summary, the degradation efficiency of aflatoxins by cold plasma is highly dependent on the plasma system used, the operating parameters applied (e.g., working gas, moisture, and energy input), exposure time, and type of food products.

Clarification of the degradation mechanism with cold plasma treatment is challenging, as plasma chemistry involves hundreds of different species and thousands of possible reactions (Hertwig, Meneses, & Mathys, 2018). Wang et al. (2015b) applied ultra-performance liquid chromatography/time-of-flight mass spectrometry (UPLC/TOF-MS) to investigate the degradation products of AFB_1. The addition reaction by the free radicals $O^{\bullet}$ and $OH^{\bullet}$ generated during RFP treatment was mainly responsible for AFB_1 decomposition. All the five degradation products lost their double bond in the terminal furan ring (Wang et al., 2015b). In another study, two degradation pathways of AFB_1 by HVACP treatment were proposed. The first pathway included several reactions in which the plasma-generated radicals, such as $H^{\bullet}$, $OH^{\bullet}$, $CHO^{\bullet}$, were joined to AFB_1. The second involved epoxidation by $HO_2^{\bullet}$ radicals and oxidation of AFB_1 through the combined effects of the oxidative species $OH^{\bullet}$, H_2O_2 and O_3. The decreased bioactivity of AFB_1 after plasma exposure was related to the loss of the double bond in difuran ring moiety, along with the modification of the lactone ring, cyclopentanone and the methoxyl group (Shi, Cooper, Stroshine, Ileleji, & Keener, 2017).

Cold plasma has been presented as a viable technology for aflatoxin decontamination in food and feed. However, this novel technology is still in the early stages of evaluation. Further research is needed to optimize plasma process conditions for different food materials. Moreover, the potential negative impacts of plasma treatment on the nutritional value and organoleptic properties of food products need to be addressed and regulated at the forefront. Finally, new plasma generating equipment, tailored for the food industry, that are easy to operate, cost effective compared with conventional approaches, and guarantee safety by adequate insulation, grounding and shielding are needed (Hertwig, Meneses, & Mathys, 2018).

3. Chemical degradation of aflatoxins

3.1. Degradation of aflatoxins with ozone

Ozone is a powerful oxidizing agent with a redox potential of 2.07 V, capable of detoxifying a wide variety of emerging contaminants in food commodities (Pandiselvam et al., 2018). Normally, ozone can be produced by several methods such as ultraviolet irradiation, electrical discharge in oxygen and electrolysis of water (Tiwari et al., 2010). Spontaneous decomposition without forming hazardous residues on treated products makes ozone a promising alternative in food processing industry. Studies on mycotoxins degradation by ozone accelerated after it was granted Generally Recognized As Safe (GRAS) status for use in food and water (FDA, 1982; 2001). Ozonation has already been successfully employed for the removal of AFB_1 in laboratory-scale trials in food, such as corn, wheat, red pepper and peanuts (Table 2). The results of sub-chronic toxicity studies on rats indicated that ozone treatment of aflatoxin-contaminated peanuts could significantly reduce hepatotoxicity and nephrotoxicity of AFB_1 (Diao, Hou, Chen, Shan, & Dong, 2013). The ozonolysis mechanism of AFB_1 involves an electrophilic attack on the double bond in difuran ring moiety, leading to the formation of a primary ozonide followed by rearrangement into molozonide derivatives such as aldehydes, ketones and organic acids (Fig. 1) (Jalili, 2016).

The ozonolysis efficiency of AFB_1 depends not only on ozone concentration and exposure time but also on the moisture content of the food matrix. For example, Luo et al. (2014a) observed an 88.1% reduction of AFB_1 in corn with 13.47% moisture content compared to a 72.4% reduction in corn with 20.37% moisture content after exposure to ozone at the concentration of 90 mg L^{-1} for 40 min. The changes in nutritional properties of food after ozone treatment should be taken into consideration. A study conducted by Wang, King, Xu, Losso, and Prudente (2008) showed that ozonation of naturally contaminated corn detoxified 92% of AFB_1 while causing a 3.2% loss in protein content. In addition, ozone was reported to change the fatty acid profile of corn (Jr. & King, 2002). However, optimization of ozone processing conditions for different food commodities to minimize its effects on quality appears to be possible. In a study of Chen et al. (2014), the conditions for degrading aflatoxins in peanuts by ozonation were optimized. A degradation rate of 65.8% was achieved in peanuts with 5% moisture content when reacted with 6.0 mg L^{-1} of ozone for 30 min at room temperature. Meanwhile, no significant differences were found in the polyphenols, resveratrol, acid value, and peroxide value between treated and untreated samples. Most of the published reports on ozonation are based on laboratory-scale processing equipment, with a limited number of studies that focused on how to scale up the process. Hence, the successful commercial application of this technology requires the development of equipment that can efficiently eliminate aflatoxins from food and feed at high-capacity and continuous mode.

3.2. Degradation of aflatoxins with electrolyzed oxidizing water

Electrolyzed oxidizing water (EOW) is generated by the passage of a dilute salt solution (~1% NaCl) through an electrolytic chamber, where the anode and cathode are separated by a membrane. The two major types of EOW are neutral electrolyzed oxidizing water (NEOW), which has a pH of 5.0–6.5, an oxidation–reduction potential (ORP) of 800–900 mV and high dissolved oxygen (DO); and acidic electrolyzed oxidizing water (AEOW), which has a pH < 3.0, a high ORP >1000 mV and high DO (Huang, Hung, Hsu, Huang, & Hwang, 2008). EOW has gained immense popularity in recent years as a novel broad-spectrum disinfectant in the food, medical and agricultural industries. EOW returns to ordinary water after use and poses no threat to humans and the environment. Chlorine and high ORP are known to be the main contributors to the sanitization effect of EOW (Rahman, Khan, & Oh, 2016). Apart from antibacterial and antifungal properties, EOW has shown promising potential for aflatoxin detoxification in agricultural products (Table 2).

Zhang, Xiong, Tatsumi, Li, and Liu (2012) observed an 85% reduction in AFB_1 level in peanuts after soaking for 15 min in AEOW. This treatment did not significantly affect the appearance and nutrient contents of peanuts. The AFB_1 degradation product following AEOW treatment was identified as AFB_1-8-chloro-9-hydroxy by high-resolution Fourier transform ion cyclotron resonance mass spectrometer (HR-FT-ICR-MS) and ^1H nuclear magnetic resonance (^1H NMR), and was determined to be devoid of mutagenicity and cytotoxicity (Xiong, Liu, & Li, 2012). In addition, the authors proposed that the high level of available chlorine concentration (ACC) in EOW was the major factor responsible for AFB_1 degradation, while ACC in the form of HCIO was probably more efficient than ACC derived from the ionic form of ClO^- in detoxifying AFB_1 (Zhang, Xiong, Tatsumi, Li, & Liu, 2012; Xiong, Liu, & Li, 2012). Jardon-Xicotencatl, Diaz-Torres, Marroquin-Cardona,

Table 2
Summary of recent studies (2010 to date) on aflatoxins degradation in food and feed with chemical treatments.

Treated sample	Treatment parameters	Aflatoxin (μg kg $^{-1}$or μg L^{-1})	Degradation (%)	Reference
Ozone				
Peanut	Gaseous ozone, 21 mg L^{-1}; Exposure for 96 h at 25 °C with flow rate of 1 L min^{-1}	AFT (190.7)	30	(de Alencar, Faroni, Soares Nde, da Silva, & Carvalho, 2012)
Peanut	Gaseous ozone, 50 mg L^{-1}; Exposure for 60 h with flow rate of 5 L min^{-1}	AFB_1 (189.5)	89.4	(Diao, Hou, Chen, Shan, & Dong, 2013)
Peanut	Gaseous ozone, 6.0 mg L^{-1}; Exposure for 30 min at room temperature	AFT (200)	65.8	(Chen et al. 2014)
Corn	Gaseous ozone, 90 mg L^{-1}; Exposure for 40 min	AFB_1 (83)	88.1	(Luo et al., 2014a)
Corn	Gaseous ozone, 75 mg L^{-1}; Exposure for 60 min	AFB_1 (53.6), AFB_2 (2.4) and AFG_1 (12.1)	86.7, 70.7 and 59.3	(Luo et al., 2014b)
Wheat	Gaseous ozone, 60 μmol mol^{-1}; Exposure for 3 h at 25 °C	AFB_1 (231.9), AFB_2 (265.8), AFG_1 (240.0) and AFG_2 (199.4)	94.6, 84.5, 80.0 and 81.0	(Savi, Piacentini, & Scussel, 2015)
Wheat	Gaseous ozone, 60 mg L^{-1}; Exposure for 5 h	AFB_1 (50), AFB_2 (50), AFG_1 (50) and AFG_2 (50)	63.2, 34.0, 54.4 and 40.3	(Trombete et al., 2017)
Poultry feed	Gaseous ozone, 5.3 mg L^{-1}; Exposure for 4 h at room temperature with flow rate of 1 L min^{-1}	AFB_1 (32.8)	86.4	(Torlak, Akata, Erci, & Uncu, 2016)
Red pepper	Gaseous ozone, 80 mg L^{-1}; Exposure for 40 min	AFB_1 (25)	74.1	(Kamber, Gülbaz, Aksu, & Doğan, 2017)
Electrolyzed oxidizing water				
Peanut	AEOW: pH 2.3, ORP 1105.6 mV, ACC 71.5 mg L^{-1}; Soaking for 15 min at room temperature	AFB_1 (34.8)	85	(Zhang, Xiong, Tatsumi, Li, & Liu, 2012)
Peanut	AEOW: pH 2.5, ACC 80 to 100 mg L^{-1}; Soaking for 15 min at 40 °C	AFB_1 (95.9)	90	(Xiong, Liu, & Li, 2012)
Peanut	NEOW: pH 5.6, ACC 60 to 100 mg L^{-1}; Soaking for 10 min at 40 °C	AFB_1 (95.9)	90	
Plant oils	AlEW: pH 12.2, ORP 861 mV; Soaking for 5 min at 20 °C	AFB_1 (40)	100	(Fan et al., 2013)
Organic acids				
Rice	1 N citric acid; Soaking for 15 min	AFT (86.3)	97.2	(Safara et al., 2010)
Black pepper	2% citric acid; Soaking for 2 h	AFB_1 (30)	29	(Jalili, Jinap, & Son, 2011)
White pepper	2% citric acid; Soaking for 2 h	AFB_1 (30)	28	
Soybean	1 N citric acid; Soaking at room temperature for 18 h	AFB_1 (7.6)	94.1	(Lee, Her, & Lee, 2015)
Plant extracts				
Corn	Aqueous extract of *Corymbia citriodora* leaf; Incubation at 30 °C and pH 8 for 72 h	AFB_1 (97.3) and AFB_2 (47.7)	91.7 and 88.8	(Iram, Anjum, Iqbal, Ghaffar, & Abbas, 2015)
Corn	Aqueous extract of *Trachyspermum ammi* seed; Incubation at 30 °C and pH 8 for 72 h	AFB_1 (97.3) and AFB_2 (47.7)	89.6 and 86.5	(Iram, Anjum, Iqbal, Ghaffar, & Abbas, 2016)
Corn	Aqueous extract of *Ocimum basilicum* leaf; Incubation at 30 °C and pH 8 for 72 h	AFB_1 (97.3) and AFB_2 (47.7)	86.9 and 83.5	(Iram et al., 2016)
Corn	Aqueous extract of *Allium sativum*, 50 μg mL^{-1}; Incubation at 25 °C for 1 h	AFB_1 (7.47)	68.3	(Negera & Washe, 2019)
Rice	Aqueous extract of *Ocimum tenuifloru*, 0.38 mg mL^{-1}; Incubation at 25 °C for 4 h	AFB_1 (1000)	42.2	(Panda & Mehta, 2013)

AFB_1, Aflatoxin B_1; AFB_2, Aflatoxin B_2; AFG_1, Aflatoxin G_1; AFG_2, Aflatoxin G_2; AFT, Total aflatoxins, the sum of AFB_1, AFB_2, AFG_1 and AFG_2. AEOW, Acidic electrolyzed oxidizing water; NEOW, Neutral electrolyzed oxidizing water; AlEW, Alkaline electrolyzed oxidizing water; ORP, Oxidation-reduction potential; ACC, Available chlorine concentration.

Villarreal-Barajas, and Mendez-Albores (2015) reported that aflatoxins content in contaminated corn was not reduced following soaking in NEOW for 15 min at room temperature, as they found no difference in the aflatoxins fluorescence level of detoxified samples as compared to untreated samples. However, cytotoxicity and genotoxicity of aflatoxins in HepG2 cells were significantly reduced upon NEOW treatment. The authors further confirmed that treatment of aflatoxin-contaminated corn with NEOW effectively alleviated aflatoxicosis in turkey poults (Gomez-Espinosa et al., 2017). In order to elucidate the degradation pathway of AFB_1 in NEOW, Escobedo-Gonzalez et al. (2016) carried out in-silico studies by density functional theory. This analysis suggested that –Cl and –OH groups of the HOCl were added to the C8 and C9 of AFB_1, yielding AFB_1-8-chloro-9-hydroxy (Escobedo-Gonzalez et al., 2016).

However, it remained unclear why retention time and fluorescence strength of AFB_1 and AFB_2 in NEOW-detoxified corn did not change. In a study of Fan et al. (2013), the combination of soaking in alkaline EOW (AlEW) with pH 12.2 and oscillation at 220 rpm for 5 min was shown to completely remove AFB_1 in edible plant oils. The degradation of AFB_1 in AlEW was attributed to the reducing potential and high pH. The benefits of EOW-based food decontamination technology, including the high efficiency, low costs, and the wide range of applicability, have been highlighted in the literature (Rahman, Khan, & Oh 2016). Further evaluation of EOW application in large volumes of naturally contaminated samples is a crucial next step leading towards widespread industrial adoption.

3.3. Degradation of aflatoxins with organic acids

Organic acids are considered as food-grade additives by most food-safety control authorities worldwide. The degradation of aflatoxins in rice, pepper and soybeans by soaking in organic acids has been studied and proved effective in laboratory experiments (Table 2). In a study by Lee, Her, and Lee (2015), soaking of contaminated soybeans in 1.0 N citric acid, lactic acid, and tartaric acid for 18 h at room temperature reduced AFB_1 by 94.1, 92.7, and 95.1%, respectively. The degradation efficiency depends on temperature, moisture content, treatment time, and acid concentration. Acidulation by citric acid reduced AFB_1 by 97% within 96 h at room temperature, while 98% reduction was achieved by boiling AFB_1 for 20 min in citric acid (Rushing & Selim, 2016). Méndez-Albores, Veles-Medina, Urbina-Álvarez, Martínez-Bustos, and Moreno-Martínez (2009) evaluated the effect of extrusion-cooking process with addition of citric acid on the degradation of aflatoxins in sorghum. The result showed that the degradation rate increased with the increase of moisture content and acid concentration. Citric acid and lactic acid hydrolyzed the double bond of difuran ring moiety in AFB_1, resulting in the formation of AFB_1-8-hydroxy as a major degradation product (Fig. 1), which exhibited reduced toxicity on HeLa cells (Aiko, Edamana, & Mehta, 2016; Rushing & Selim, 2016). The high level of organic acids in fruit juices makes them natural and readily available sources for the degradation of AFB_1 in contaminated food. Rastegar et al. (2017) reported a 50.2% AFB_1 degradation in pistachio nuts after roasting with lemon juice at 120 °C for 60 min. Acidulation can be coupled with other techniques for synergistic effects. Abuagela et al. (2019) recently investigated the efficiency of combing acidulation followed by pulsed light treatment on aflatoxins detoxification in peanuts. This combination approach degraded aflatoxins up to 98.3%, whereas citric acid or pulsed light individually only reduced aflatoxins by 20.2 and 78.1%, respectively. Despite the leaching of nutrients like minerals, starch and water-soluble proteins into the soaking medium, changes in the chemical composition of cereal grains after soaking in organic acids may have additional benefits on the health and performance of livestock animals. Treating barley grain with 5% lactic acid has been shown to increase the content of resistant starch (RS), a functional prebiotic that can potentially stimulate hindgut fermentation and reduce the risk of metabolic diseases (Deckardt, Khiaosa-ard, Grausgruber, & Zebeli, 2014). Soaking of cereals in lactic acid can also favor the hydrolysis of phytate phosphorus, thus improving the availability of phosphorus in cereals for monogastric animals (Metzler-Zebeli, Deckardt, Schollenberger, Rodehutscord, & Zebeli, 2014; Vötterl, Zebeli, Hennig-Pauka, & Metzler-Zebeli, 2019). However, the high cost of organic acids restricts its applicability in feed manufacturing.

3.4. Degradation of aflatoxins with plant extracts

Natural plant extracts have been widely used as food additives and pharmaceuticals since ancient times for their anti-microbial, anti-inflammation, anti-oxidation, and immune boosting activities. The potential use of natural plant extracts in mycotoxin detoxification has received much attention in recent years. Vijayanandraj et al. (2014) investigated aqueous extracts of 31 medicinal plants for their ability to detoxify AFB_1. They found that among the different plant extracts, the leaf extract of *Adhatoda vasica* Nees showed the highest AFB_1-detoxifying activity with a degradation efficiency as high as 98% after incubation at 37 °C for 24 h. The same group of researchers also demonstrated that pre-feeding rats with spray-dried formulation of *Adhatoda vasica* Nees leaf extract could counteract the hepatotoxicity induced upon subsequent exposure to AFB_1 (Brinda et al., 2013). In a recent study, Ponzilacqua, Rottinghaus, Landers, and Oliveira (2019) noticed a time-dependent degradation of AFB_1 following incubation in aqueous leave extracts of *Rosmarinus officinalis*, with a maximum AFB_1 reduction of 60.3% after 48 h incubation. Moreover, some studies have demonstrated the effectiveness of natural plant extracts in eliminating aflatoxins from rice and corn as shown in Table 2. Panda and Mehta (2013) reported that a 42.2% reduction of AFB_1 level in rice could be achieved after incubation with an aqueous extract of *Ocimum tenuiflorum* at 25 °C. Moreover, aqueous extracts of *Corymbia citriodora* and *Trachyspermum ammi* were also studied for degrading AFB_1 and AFB_2 in contaminated corn (Iram, Anjum, Iqbal, Ghaffar, & Abbas, 2015; Iram, Anjum, Iqbal, Ghaffar, & Abbas, 2016). The authors found that AFB_1 and AFB_2 in spiked corn samples were degraded up to 91.7 and 88.8%, respectively, by *C. citriodora* leaf extract, while AFB_1 and AFB_2 levels were reduced by 89.6 and 86.5%, respectively, after treatment with *T. ammi* seeds extract. Mass spectrometry analysis of the degradation products confirmed that treatment with *C. citriodora* leaf extract led to lactone group modification and removal of the double bond in the difuran ring moiety of AFB_1 (Iram, Anjum, Iqbal, Ghaffar, & Abbas, 2015). Similar findings were also observed after detoxification of AFB_1 and AFG_1 by *T. ammi* seeds extract (Iram, Anjum, Iqbal, Ghaffar, & Abbas, 2016; Velazhahan et al., 2010). Brine shrimp lethality assay further confirmed much lower toxicity of degraded products compared with that of AFB_1 (Iram, Anjum, Iqbal, Ghaffar, & Abbas, 2015; Iram, Anjum, Iqbal, Ghaffar, & Abbas, 2016).

Plant extracts are very complex mixtures, and their components varies with plant species and chemotype, phonological stage, tissue, and method of extraction (Figueiredo, Barroso, Pedro, & Scheffer, 2008). There has been little in-depth research to identify active compounds in plant extracts responsible for the observed detoxification of aflatoxins. A preliminary study showed that partially purified alkaloids from *Adhatoda vasica* Nees leaf extract exhibited strong AFB_1 detoxification activity (Vijayanandraj et al., 2014). It should also be noted that aflatoxin degradation with plant extracts could be the result of various compounds working a multi-step process. Further studies are needed to provide deeper insight into the action model as well as the potential interactions of natural plant extracts with food and feed matrices.

4. Biological degradation of aflatoxins

Scientists have come to favor the use of biological methods for the degradation of aflatoxins. This method takes the form of microbial or enzymatic transformation of aflatoxins into non-toxic or less toxic metabolites. A number of microorganisms from various sources such as soil, water, animal excreta and even contaminated food materials have been reported to be capable of degrading aflatoxins (Table 3). To gain further insights into microbial degradation, researchers are now focusing on the identification of functional genes and purification of aflatoxin-degrading enzymes. The use of microbes as well as isolated enzymes for the removal of aflatoxins in food and feed is an efficient, specific, and environmentally friendly decontamination strategy.

4.1. Microbial degradation of aflatoxins

A number of *Pseudomonas* strains, such as *P. putida* 12–3 (Elaasser & El Kassas, 2011), *P. aeruginosa* N17-1 (Sangare et al., 2014), and *P. anguilliseptica* VGF1 (Adebo, Njobeh, Sidu, Tlou, & Mavumengwana, 2016) have been reported to be capable of degrading aflatoxins. The

Table 3
Summary of aflatoxin-degrading microoganisms over the last ten years.

Microoganism	Source	Degradation condition	AFB_1(μg kg^{-1}or μg L^{-1})	Degradation (%)	Reference
***Pseudomonas* spp.**					
P. putida 12–3	Drainage	30 °C for 72 h in cell culture supernatant	100	83.3	(Elaasser & El Kassas, 2011)
P. putida 1274	MTCC	30 °C for 24 h in MSG medium inoculated with cell suspensions	200	90	(Samuel, Sivaramakrishna, & Mehta, 2014)
P. putida 2445	MTCC	30 °C for 24 h in MSG medium inoculated with cell suspensions	200	90	
P. aeruginosa N17-1	Soil	37 °C for 72 h in cell culture	100	82.8	(Sangare et al., 2014)
P. anguilliseptica VGF1	Groundwater in gold mine	37 °C for 12 h in cell lysate	500	100	(Adebo, Njobeh, Sidu, Tlou, & Mavumengwana, 2016)
P. fluorescen	Groundwater in gold mine	37 °C for 12 h in cell lysate	500	100	
***Rhodococcus* spp.**					
R. globerulus AK36	Oil contaminated soil	28 °C for 72 h in LB medium inoculated with cell suspensions	2000	95	(Cserháti et al., 2013)
R. corynebacterioides JCM3376	JCM	28 °C for 72 h in LB medium inoculated with cell suspensions	2950	100	(Risa et al., 2018)
R. rhodochorus NI2	Hydrocarbon contaminated site	28 °C for 72 h in LB medium inoculated with cell suspensions	2000	99.1	(Krifaton et al. 2011)
R. erythropolis ATCC 4277	ATCC	30 °C for 24 h in Difco ISP medium No. 1 inoculated with cell suspensions	810	96	(Eshelli, Harvey, Edrada-Ebel, & McNeil, 2015)
R. erythropolis 4.1491	CGMCC	23.2 °C for 81.9 h in ATYP medium inoculated with cell suspensions	50	95.8	(Kong et al., 2012)
***Streptomyces* spp.**					
S. lividans TK 24	SIPBS	30 °C for 24 h in Difco ISP medium No. 1 inoculated with cell suspensions	810	88	(Eshelli, Harvey, Edrada-Ebel, & McNeil, 2015)
S. aureofaciens ATCC 10762	ATCC	30 °C for 24 h in Difco ISP medium No. 1 inoculated with cell suspensions	810	86	
S. cacaoi subsp. *asoensis* K234	NP	28 °C for 5 days in LB medium inoculated with cell suspensions	1000	88.3	(Harkai et al., 2016)
***Bacillus* spp.**					
B. subtilis ANSB060	Fish intestinal chyme	37 °C for 72 h in cell culture	100	81.5	(Gao et al., 2011)
B. subtilis UTBSP1	Pistachio nut	30 °C for 5 days in pistachio ground kernel inoculated with cell suspensions	2500	95	(Farzaneh et al., 2012)
B. subtilis JSW-1	Soil	30 °C for 72 h in cell culture supernatant	2500	62.8	(Xia et al., 2017)
B. licheniformis CFR1	Fallow deer faeces	37 °C for 72 h in cell culture supernatant	500	93.6	(Raksha Rao, Vipin, Hariprasad, Anu Appaiah, & Venkateswaran, 2017)
B. licheniformis BL010	AFB_1 contaminated soil	30 °C for 24 h in cell lysate	50,000	93.6	(Wang et al., 2018b)
B. velezensis DY3108	Soil	30 °C for 72 h in cell culture supernatant	500	82.0	(Shu et al., 2018)
B. shackletonii L7	Soil	37 °C for 72 h in cell culture	100	92.1	(Xu et al., 2017)
B. mojavensis RC3B	Pond mud	30 °C for 72 h in cell culture supernatant	179.4	75.3	(Gonzalez Pereyra, Martinez, & Cavaglieri, 2019)
B. cereus RC1C	Pond mud	30 °C for 72 h in cell culture supernatant	179.4	77.2	
Bacillus sp. TUBF1	AFB_1 contaminated corn	30 °C for 24 h in cell culture supernatant	10,000	100	(El-Deeb, Altalhi, Khiralla, Hassan, & Gherbawy, 2013)
Escherrichia coli					
E. coli 12–5	Drainage	30 °C for 72 h in cell culture supernatant	100	62.5	(Elaasser & El Kassas, 2011)
E. coli CG1061	Chicken cecum chyme	37 °C for 72 h in cell culture supernatant	2500	91.9	(Wang et al., 2018a)
***Pleurotus* spp.**					
P. eryngii ITEM 13681	ITEM	30 °C for 28 days in corn inoculated with cell suspensions	500	86	(Brana, Cimmarusti, Haidukowski, Logrieco, & Altomare, 2017)
P. ostreatus GHBBF10	Decomposing tree trunk	30 °C for 15 days in rice straw inoculated with cell suspensions	500	91.8	(Das, Bhattacharya, Palaniswamy, & Angayarkanni, 2014)
P. ostreatus MTCC 142	MTCC	30 °C for 15 days in rice straw inoculated with cell suspensions	500	89.1	
P. ostreatus N001	CECT	In corn inoculated with cell suspensions	2500	91.5	(Jackson & Pryor, 2017)
Aspergillus niger					
A. niger ND-1	Feedstuff	32 °C for 24 h in culture supernatant	10	43.4	(Zhang et al., 2014)
A. niger FS-UV1	CCTCC	30 °C for 48 h in liquid culture of immobilized cells	50	95.3	(Sun et al., 2016)

MTCC, Microbial Type Culture Collection & Gene Bank, India; JCM, Japan Collection of Microorganism; ATCC, American Type Culture Collection; CGMCC, China General Microbiological Culture Collection Center; SIPBS, the Institute of Pharmacy and Biomedical Sciences collection at the University of Strathclyde, Glasgow, UK; ITEM, the Culture Collection of the Institute of Sciences of Food Production, Bari, Italy; CECT, Spanish Type Culture Collection; CCTCC, China Center for Type Culture Collection. NP, not provided; AFB_1, Aflatoxin B_1.

abilities of *P. putida* MTCC1274 and *P. putida* MTCC2445 to remove AFB_1 from culture medium were investigated by Samuel, Sivaramakrishna, and Mehta (2014), and the results showed that both strains of *P. putida* degraded more than 90% of AFB_1 during an incubation period for 24 h. Gas chromatography mass spectrometry (GC–MS) and fourier transform infrared spectroscopy (FT-IR) analyses revealed that the lactone ring of AFB_1 was modified by *P. putida*, yielding three non-fluorescent compounds (AFD_1, $C_{16}H_{14}O_5$; AFD_2, $C_{17}H_{14}O_6$; and AFD_3, $C_8H_4O_3$). Moreover, the *in vitro* cytotoxicity test on HeLa cells showed that all these metabolites are less toxic when compared with AFB_1.

A preliminary study by Cserháti et al. (2013) investigated the mycotoxin degradation ability of thirty-two *Rhodococcus* strains. The

results showed that 59% of the investigated *Rhodococcus* strains could degrade more than 90% of AFB_1 and remove its genotoxicity. Thin layer chromatography (TLC) analysis confirmed the cleavage of the lactone group of AFB_1 by *R. erythropolis* ATCC 4277 (Eshelli, Harvey, Edrada-Ebel, & McNeil, 2015). Prettl et al. (2017) evaluated the potential use of *R. pyridinivorans* K408 to detoxify AFB_1 in corn-based whole stillage, and found that the AFB_1 level in solid and liquid phases of the whole stillage was eliminated by 63 and 75%, respectively.

Examination of one hundred and twentyfour *Streptomyces* strains for mycotoxin degradation showed that 55% of the *Streptomyces* strains tested were able to degrade AFB_1 (Harkai et al., 2016). The decrease in AFB_1 concentration ranged from 1.6 to 88.3%. In another work, *S. lividans* TK 24 was found to degrade 88% of AFB_1 in liquid culture following a 24 h incubation (Eshelli et al., 2015).

Several studies have reported that *Bacillus* species can be used to degrade aflatoxins. *B. subtilis* ANSB060, isolated from fish gut, was able to degrade AFB_1, AFG_1 and AFM_1 in liquid culture by 81.5, 80.7 and 60.0%, respectively, after 72 h of incubation (Gao et al., 2011). Likewise, Farzaneh et al. (2012) reported the ability of *B. subtilis* UTBSP1 to degrade up to 95% of AFB_1 in pistachio nuts after 5 days of treatment. In another study, it was shown that cell-free supernatant of *B. subtilis* JSW-1 had the ability to detoxify 62.8% of AFB_1 within 72 h (Xia et al., 2017). Several studies have also reported the degradation of AFB_1 by other *Bacillus* isolates, including *B. licheniformis* CFR1 (Raksha Rao, Vipin, Hariprasad, Anu Appaiah, & Venkateswaran, 2017), *B. licheniformis* BL010 (Wang et al., 2018b), *B. velezensis* DY3108 (Shu et al., 2018) and *Bacillus* sp. TUBF1 (El-Deeb, Altalhi, Khiralla, Hassan, & Gherbawy, 2013). *B. subtilis* has been approved as GRAS bacterial strains for nutritional and pharmaceutical use. Moreover, *B. subtilis* is capable of forming spores resistant to heat and low gastric pH. A commercial microbial feed additive consisting of the fermentation product of *B. subtilis* ANSB060 has been approved for commercialization in China. Most impressively, dietary supplementation of this direct-fed microbial product has been confirmed to be effective in alleviating aflatoxicosis in laying hens (Ma et al., 2012), chickens (Fan et al., 2015), ducks (Zhang et al., 2016), carps (Fan et al., 2018) and dairy cows (Guo et al., 2019).

The first evidence of the ability of *Escherichia coli* to degrade AFB_1 was reported by Elaasser and El Kassas (2011). In their study, culture supernatant of *E. coli* 12–5 was able to degrade 62.5% of AFB_1 after 72 h incubation compared to 38.3, 14.8 and 5.6% by viable cells, dead cells and cell extracts, respectively (Elaasser & El Kassas, 2011). Similarly, Wang et al. (2018a) isolated an AFB_1 detoxifying bacterium *E. coli* CG1061 from chicken cecum. It was found that the bacterium could degrade 93.7% of AFB_1 within 72 h, resulting in the formation of a range of lower molecular weight degradation products.

Previous research has also suggested the capability of some white-rot fungi from the genus *Pleurotus* to detoxify aflatoxins. The ability of *P. eryngii* ITEM 13681 to degrade AFB_1 under laboratory-scale mushroom cultivation was investigated by Brana, Cimmarusti, Haidukowski, Logrieco, and Altomare (2017). The mushroom growth medium contained 25% (w/w) of corn spiked with AFB_1 to a final concentration of 128 μg kg^{-1}. *P. eryngii* ITEM 13681 reduced the level of AFB_1 in culture medium by 86% after 28 days, with no significant reduction of either biological efficiency or mushroom yield. Likewise, Jackson and Pryor (2017) found no aflatoxin residues in *P. ostreatus* mushrooms produced from AFB_1-contaminated corn.

The use of non-toxigenic *Aspergillus niger* in the food industry comes primarily from its production of various enzymes like amylase, amyloglucosidase, lactase, cellulases, pectinases, invertase, and acid proteases. Strains of *Aspergillus niger* with aflatoxin degradation ability were also selected and characterized in previous studies. Zhang et al. (2014) found that culture supernatant of *A. niger* ND-1 degraded 43.4% of AFB_1 after incubation at 32 °C for 24 h. In a study of Sun et al. (2016), *A. niger* FS-UV1, derived from wild strain *A. niger* FS-Z1 by mutagenic treatment with UV irradiation, displayed a superior AFB_1 degradation rate, reaching up to 95.3%. The results of Ames test indicated that the mutagenic activity of AFB_1 was greatly abated after treatment with *A. niger* FS-UV1. Moreover, the hepatotoxicity and nephrotoxicity of AFB_1 in rats could be alleviated by dietary supplementation with immobilized *A. niger* FS-UV1 cells.

Microbial consortium can be constructed using bacteria, fungi or both. There are complex and intricate networks of communication in microbial communities, which play decisive role in the adaptation of microbes in the presence of xenobiotic compounds. Wang et al. (2017) developed a thermophilic microbial consortium TADC7 with stable and efficient AFB_1 degradation activity. Cell-free supernatant of TADC7 consortium showed AFB_1 degradation rate of more than 95% in a wide temperature range from 50 to 90 °C. According to 16S rDNA sequencing analysis, *Geobacillus* and *Tepidimicrobium* may play major roles in AFB_1 degradation by TADC7 consortium.

4.2. Enzymatic degradation of aflatoxins

Important technological advances in the field of molecular biology have allowed scientists to isolate and identify aflatoxin-degrading enzymes from microbes. A schematic diagram describing the workflow of research on aflatoxin-degrading enzymes is shown in Fig. 2. Biodegradation based on cell-free enzyme preparations avoids the shortcoming of applying whole microorganisms, which aparts from their degradation activity, may impair the organoleptic properties of food commodities and produce undesirable compounds (Adebo, Njobeh, Gbashi, Nwinyi, & Mavumengwana, 2017). Previous studies have documented that aflatoxins could be degraded by laccases, peroxidases, oxidases and reductases. The reaction mechanisms for AFB_1 detoxification catalyzed by aflatoxin-degrading enzymes are summarized in Fig. 3.

Laccases are a class of blue multicopper enzymes capable of oxidizing a wide variety of phenolic and non-phenolic aromatic compounds while reducing molecular oxygen in water. Laccases are widespread in nature, occurring in bacteria, fungi, higher plants and insects. The use of fungal laccases in AFB_1 decontamination was first proposed by Alberts, Gelderblom, Botha, and van Zyl (2009). The research group successfully employed pure laccase from *Trametes versicolor* and a recombinant laccase produced by *A. niger* to degrade AFB_1. The treatment of AFB_1 with *T. versicolor* laccase resulted in a 59% reduction in prooxidative properties and complete elimination of genotoxicity (Zeinvand-Lorestani et al., 2015). The catalytic capacity of laccase enzyme can be greatly improved by combining it with redox mediators, which serve as electron shuttles between laccase and target substrate. The AFB_1 degradation by Lac2 laccase from *Pleurotus pulmonarius* was remarkably enhanced by 23 to 99% with the addition of 10 mM acetosyringone (AS) as a redox mediator (Loi et al., 2016). Oxidation of AFB_1 following 72-h incubation with Ery4 laccase from *Pleurotus eryngii* was evaluated in the presence of eight different redox mediators. The results showed that syringl-type phenols acetosyringone (AS) and syringaldehyde (SA) were the best performing mediators with degradation percentages of 73 and 68%, while hydroxybenzotriazole (HBT), phenol red (PhR) and 2, 2, 6, 6-tetramethylpyperidyloxil (TEMPO) were less or totally non-efficient in AFB_1 degradation (Loi et al., 2018). Compared with fungal laccases, bacterial laccases exhibit notable features of high thermostability, wide pH range, broad substrate spectrum and tolerance to alkaline conditions (Guan, Luo, Wang, Chen, & Liao, 2018), which make bacterial laccases excellent candidates for the degradation of xenobiotics. Recently, Guo et al. (2020) reported that *B. licheniformis* CotA laccase could catalyze the C3-hydroxylation of AFB_1, and the transformation products aflatoxin Q_1 and epi-aflatoxin Q_1 were non-toxic to human liver cells L-02. The CotA laccase was highly thermostable with a half-life of 1 h at 70 °C, and the enzyme could degrade more than 70% of AFB_1 in temperature range from 60 to 80 °C within 30 min. Molecular docking simulation predicted that AFB_1 interacted with CotA laccase through hydrogen bonding and van der Waals interaction.

Peroxidases represent a large family of oxidoreductase enzymes that can catalyze the oxidation of various electron donor substrates with the

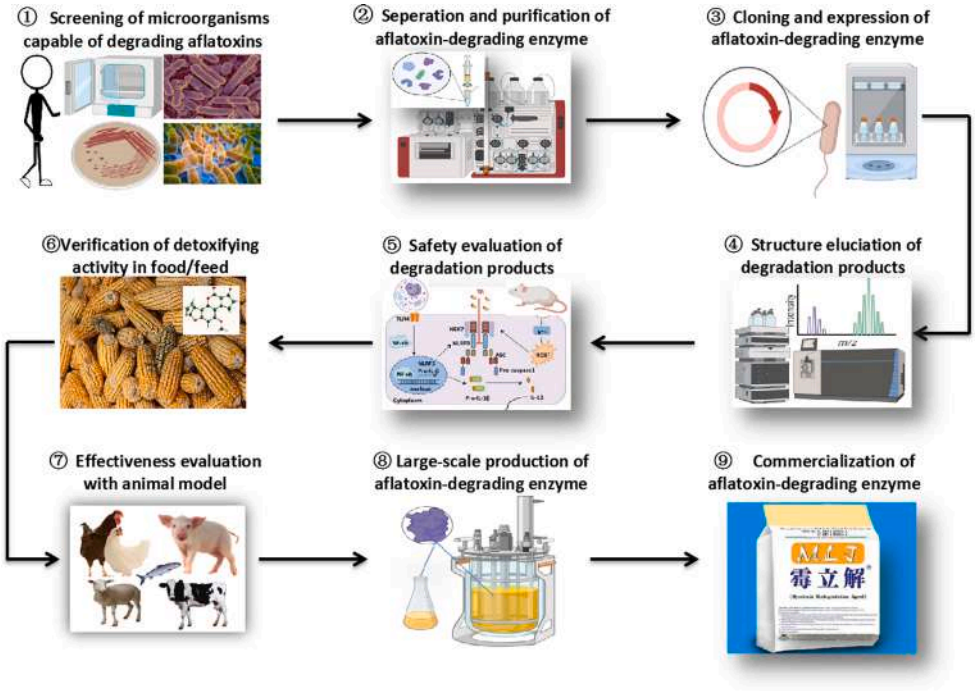

Fig. 2. Workflow of research on aflatoxin-degrading enzymes.

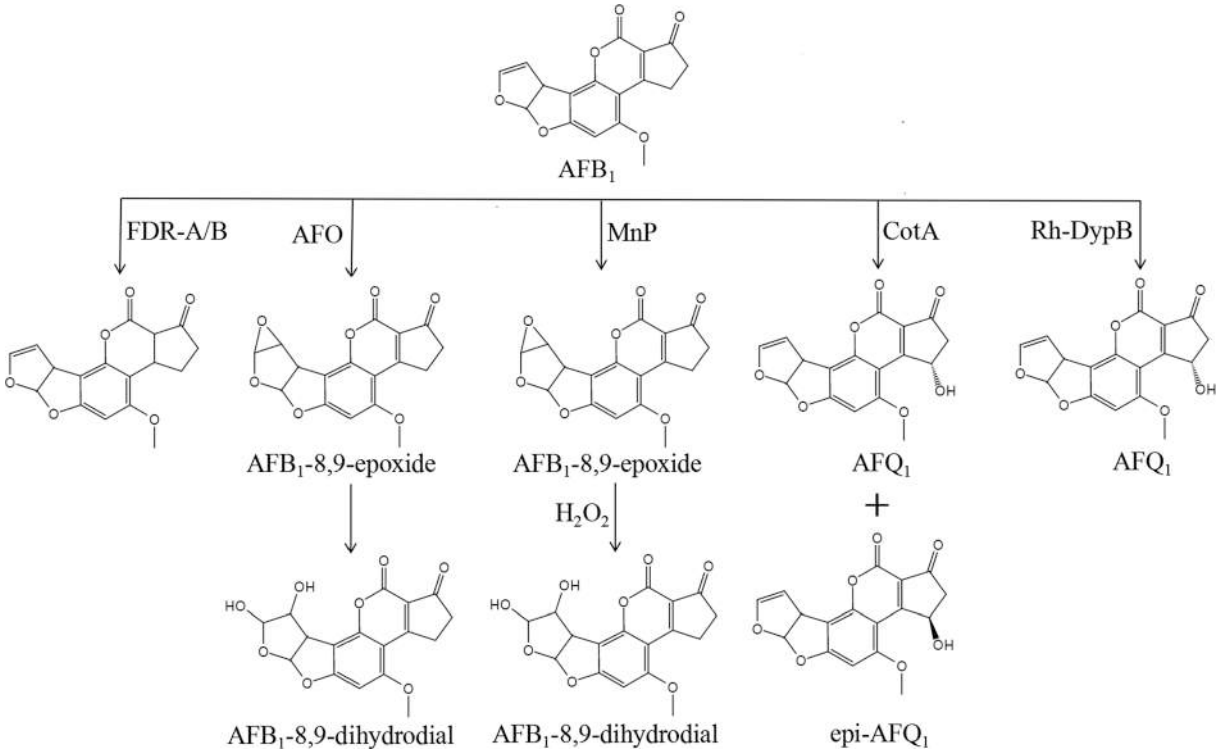

Fig. 3. The degradation pathways of AFB_1 by aflatoxin-degrading enzymes.

concomitant decomposition of H_2O_2. A vast majority of peroxidases are heme-containing and ubiquitously present in prokaryotes and eukaryotes. Enzymatic degradation of aflatoxins by peroxidases derived from various sources has been reported. Das and Mishra (2000) achieved a 53% AFB_1 reduction in groundnut meal by using horse radish peroxidase (HRP). In addition, Marimón Sibaja et al. (2018) reported that HRP reduced AFB_1 and AFM_1 levels by 97 and 65%, respectively, in milk after 8 h at 30 °C. In a study of Tripathi and Mishra (2009), a 70% degradation of AFB_1 in red chili powder was observed upon treatment with garlic peroxidase for 30 h. Wang, Ogata, Hirai, and Kawagishi (2011) examined the ability of manganese peroxidase (MnP) from white-rot fungus *Phanerochaete sordida* YK-624 in degrading AFB_1. The study showed that the enzyme was able to degrade 86.0% of AFB_1 and reduced its mutagenic activity by 69.2%. Based on ^1H NMR and high resolution electrospray ionization mass spectrometry (HR-ESI-MS) analysis, the authors proposed that AFB_1 was first oxidized to an epoxide

intermediate AFB_1-8, 9-epoxide by MnP, and then hydrolyzed to AFB_1-8, 9-dihydrodiol accompanied by H_2O_2 addition (Wang, Ogata, Hirai, and Kawagishi, 2011). Furthermore, Wang et al. (2019) revealed that AFB_1 degradation by MnP was achieved by free radical attack, which shared the same mechanism of MnP-mediated dye decolorization. The rate of AFB_1 degradation by different MnPs was positively related to their ability to decolorize reactive black 5. As a new family of microbial peroxidases, dye-decolorizing peroxidases (DyP) were named for their ability to efficiently oxidize synthetic anthraquinone and azo-dyes. Loi et al. (2020) recently reported that the type B dye decolorizing peroxidase (Rh_DypB) from *Rhodococcus jostii* could degrade up to 96% of AFB_1 in sodium malonate buffer, resulting in the formation of AFQ_1 as major transformation product.

Liu et al. (1998; 2001) isolated and purified an aflatoxin detoxifizyme (ADTZ) from the mushroom *Armillariella tabescens*. The enzyme was subsequently identified and renamed aflatoxin oxidase (AFO) (Cao, Liu, Mo, Xie, & Yao, 2011). Bioinformatic analysis showed that AFO shared 42% amino acid sequence similarity with dipeptidyl peptidase III (DPP III), a zinc-dependent hydrolase from M49 family of metallopeptidases (Wu et al., 2015). Further investigation confirmed that AFO was a dual activity enzyme with both aflatoxin-oxidase and dipeptidyl peptidase activities (Xu, Xie, Yao, Zhou, & Liu, 2017). AFO was also able to act on versicolorin A, 3, 4-dihydro-2H-pyran and furan which shared the structure of furan or pyran ring with AFB_1, indicating that double bond in difuran ring moiety of AFB_1 was the potential action site for AFO (Wu et al., 2015). During this reaction, H_2O_2 was produced with water as the hydrogen donor (Wu et al., 2015). It was worth noting that Guan and colleagues successfully expressed AFO in the parotid gland of mice and pigs, and confirmed that AFO in the saliva could effectively eliminate the toxicity of AFB_1 in transgenic mice and pigs (Guan et al., 2015; Lou et al., 2017). These findings pave a new way for the application of aflatoxin-detoxifizyme gene in breeding animal species with aflatoxin resistance.

Taylor et al. (2010) identified and characterized nine $F_{420}H_2$-dependent reductases (FDRs) from *Mycobacterium smegmatis* that utilized the deazaflavin cofactor $F_{420}H_2$ to catalyze the reduction of the α, β-unsaturated ester moiety of aflatoxins. These enzymes fall into two classes (FDR-A and -B), and the class of FDR-A enzymes has up to 100 times more activity than the FDA-B class (Lapalikar et al., 2012). In a recent investigation, Li et al. (2019) showed that DNA damage and p53-mediated apoptosis in HepG2 cells exposed to AFB_1 could be significantly reduced by the addition of the recombinant FDR-A enzyme MSMEG-5998 in culture medium.

Academics have been working continuously to explore novel aflatoxin-degrading enzymes. Zhao et al. (2011) purified a 32 kDa extracellular enzyme MADE from *Myxococcus fulvus*. The optimum condition for the AFB_1-degrading activity of MADE was observed at pH 6.0 and 35 °C. The purified MADE could also degrade AFM_1 and AFG_1 by 96 and 97% after 48 h of incubation. Similar studies on a purified enzyme BADE from *Bacillus shackletonii* showed that the enzyme was able to degrade 48% of AFB_1 at 70 °C after 72 h (Xu et al., 2017). Importantly, BADE was highly thermostable and retained its activity after boiling at 100 °C for 10 min. The authors speculated that BADE was an oxidoreductase that utilized copper ion as an activator. The AFB_1-degrading activity of BADE was significantly improved in the presence of copper ion. However, the amino acid sequences of MADE and BADE have not been reported. In a more recent study, Xie, Wang, and Zhang (2019) isolated a 38 kDa AFB_1-degrading enzyme PADE from *Pantoea* sp. T6, which was matched to the outer membrane protein A (OmpA) in the Uniprot database (Accession No. A0A1X1BYP1) by peptide mass fingerprint analysis. The catalytic function of OmpA has not been reported in previous studies. Further investigation is required to understand the AFB_1 degradation activity of *Pantoea* sp. T6 OmpA.

While these aflatoxin-degrading enzymes are effective, there are practical obstacles to their application in food and feed industry. One of the main problems is the low production yields of these enzymes in their native hosts. Thus, it would be economically unfeasible to produce them using standard fermentation or culture techniques. However, production of these enzymes using recombinant DNA technologies could address this issue. On the other hand, modern food and feed processing tends to be sophisticated and precise, and generally requires high temperature, extreme pH, and the use of solvents (Zhang, Geary, & Simpson, 2019). However, the stability and catalytic efficiency of wild-type enzymes under stress conditions is less than satisfactory. The recently developed enzyme engineering technologies like random mutagenesis and directed evolution will open the gate to the improvement of properties of aflatoxin-degrading enzymes. Biological agents to be used in practice as animal feed additives must rapidly degrade mycotoxins into non-toxic metabolites, under different oxygen conditions and in a complex environment (Boudergue et al. 2009). Up to now, there is still lack of scientific methods standardized to investigate the activity of mycotoxin-degrading enzymes in the digestive systems of animals. *In vitro* models mimicking the digestive process in the gastric-intestinal tract have been proposed to assess the effects of different feed enzymes (phytase, xylanase, and β-glucanase) on release of trace elements in feedstuffs (Yu, Han, Li, Zhang, & Feng, 2018). Thus, it is possible to develop *in vitro* models to evaluate the efficiency of aflatoxin-degrading enzymes in reducing the bioavailability of aflatoxins in the digestive tract of animals.

5. Future perspective of nanozymes in aflatoxins degradation

Given the diverse nature of the food and feed industry, there is the need for the development of novel technologies for sustainability, safety, profitability, and to gain consumer trust (Pal et al., 2016). Nanozymes refer to nanomaterials with enzyme-mimicking activity, which can catalyze the conversion of substrates and follow the same kinetics and mechanisms as natural enzymes under physiological conditions (Wei & Wang, 2013). Since the discovery of Fe_3O_4 nanoparticles with intrinsic peroxidase-like activity in 2007 (Gao et al., 2007), a large number of studies on nanozymes have emerged. Compared with natural enzymes, nanozymes show better stability and durability due to the inherent properties of nanomaterial. Inspired by the structure of the active site and the electron transfer pathway of laccases, Liang et al. (2017) prepared a laccase-mimicking nanozyme by coordinating guanosine monophosphate (GMP) with Cu^{2+} to form amorphous metal–organic framework (MOF) nanomaterial. The preparation of Cu/GMP nanozyme is very simple with a mixture of two common chemicals at room temperature. The Cu/GMP nanozyme is about 2400-fold more cost-effective than commercial protein laccase in achieving the same catalytic efficiency. Moreover, the Cu/GMP nanozyme is robust against extreme pH, temperature, salt, and long-term storage. Considering that both bacterial and fungal laccases exhibit AFB_1 oxidation capacity, it is of great interest to evaluate the potential use of this Cu/GMP nanozyme in AFB_1 removal.

Up to now, several nanomaterials with peroxidase-like activity have been constructed such as $Pt_{74}Ag_{26}$ nanoparticle-decorated ultrathin MoS_2 nanosheets (Cai et al., 2016), FePt nanoparticle-decorated graphene oxide nanosheets (Chen et al., 2018), $FeMnO_3$ nanoparticle-filled polypyrrole nanotubes (Chi, Chen, Zhong, Wang, & Lu, 2018), and $CuMnO_2$ nanoflakes (Chen, Chen, Wu, & Yang, 2019). An interesting attempt was made by Ren, Luo, and Wan (2019) using peroxidase-like Fe-based MOFs for the degradation of AFB_1. The MOFs was able to degrade more than 85% of AFB_1 at the initial concentration of 50 μg mL^{-1}. Corn starch, corn oil and cellulose have little impact on the ability of peroxidase-like catalytic system to degrade AFB_1. The hepatotoxicity of AFB_1 is detoxified by peroxidase-like MOFs as AFB_1 is transformed into a variety of low-carbon compounds· H_2O_2 is required for peroxidase-catalyzed degradation of xenobiotic compounds. With molecular oxygen as an electron acceptor, glucose oxidase (GOx) can catalyze the oxidation of β-D-glucose to D-glucono-δ-lactone and H_2O_2, which is an easy way to generate H_2O_2 in food commodities. Thus, the GOD and peroxidase cascade reaction could be an ideal strategy for

degrading AFB_1 in real food systems. Hou et al. (2015) developed a mimetic multi-enzyme system by embedding GOx in a mimetic peroxidase zeolitic imidazolate framework 8 (mZIF-8), which showed highly catalytic activity and sensitivity to glucose, and the produced H_2O_2 could be immediately decomposed by the support mZIF-8 to oxidize o-phenylenediamine. Moreover, the mZIF-8@GOx exhibited excellent reusability, retaining about 88.7% residual activity after 12 times reuse. These research advances will pave the way for the development of nanozyme-based antidotes to aflatoxins in the coming years.

6. Conclusion

Aflatoxin contamination in agricultural commodities is of worldwide concern, both for its negative impacts on human and animal health and the considerable economic loss to the food and feed industry. The growing consumer demand for safe and high quality food has driven scientists to develop effective degradation technologies for this carcinogenic food contaminant. Despite the intensive research in this field and of the numerous publications that show the success of various physical, chemical and biological approaches, the results achieved till date can only be considered as the first step in the development of commercially feasible technologies. Several criteria must be met by methods suitable for industrilization: (1) effectively and rapidly reduce aflatoxins to acceptable levels; (2) not produce or leave toxic residues in food and feed; (3) retain the nutritive value and sensory properties of food and feed; (4) be economically feasible and environmentally friendly; and (5) if possible, destroy fungal spores. Studies involving irradiation and cold plasma have led to encouraging outcomes, but the majority of experiments are performed in model systems and in laboratory conditions. The applicability of ozone, electrolyzed oxidizing water, organic acids and plant extracts depends not only on their efficacy and safety, but also on consumer acceptance. In our opinion, biodegradation using probiotics as well as isolated enzymes has good potential for large-scale applications. A number of studies have confirmed both *in vitro* and *in vivo* detoxification capacity of probiotic *Bacillus* species, which can be directly incorporated into feed to protect farm animals from aflatoxicosis. Fermented food products have a long tradition in Southeast Asia where there is remarkable market opportunity for aflatoxin-free fermented food by using aflatoxin-degrading probiotics as fermenting microbes. Many enzymes such as protease, amylase, lipase, phytase, glucose oxidase and others have been successfully applied in the food and feed industry. Thus, the adoption of cost-effective aflatoxin-degrading enzymes with high efficiency and specificity for post-harvest aflatoxin decontamination can be expected in the near future.

CRediT authorship contribution statement

Yongpeng Guo: Investigation, Data curation, Writing - original draft. **Lihong Zhao:** Supervision, Writing - review & editing, Funding acquisition. **Qiugang Ma:** Validation. **Cheng Ji:** Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by National Natural Science Foundation of China (Program No. 31972604 and 31772637). Yongpeng Guo would like to thank his family for their support and encouragement when he was grounded at home due to the outbreak of COVID-19 to prepare this review paper.

References

Abuagela, M. O., Iqdiam, B. M., Baker, G. L., & MacIntosh, A. J. (2018). Temperature-controlled pulsed light treatment: Impact on aflatoxin level and quality parameters of peanut oil. *Food and Bioprocess Technology, 11*(7), 1350–1358.

Abuagela, M. O., Iqdiam, B. M., Mostafa, H., Gu, L., Smith, M. E., & Sarnoski, P. J. (2018). Assessing pulsed light treatment on the reduction of aflatoxins in peanuts with and without skin. *International Journal of Food Science and Technology, 53*(11), 2567–2575.

Abuagela, M. O., Iqdiam, B. M., Mostafa, H., Marshall, S. M., Yagiz, Y., Marshall, M. R., … Sarnoski, P. (2019). Combined effects of citric acid and pulsed light treatments to degrade B-aflatoxins in peanut. *Food and Bioproducts Processing, 117*, 396–403.

Adebo, O. A., Njobeh, P. B., Gbashi, S., Nwinyi, O. C., & Mavumengwana, V. (2017). Review on microbial degradation of aflatoxins. *Critical Reviews in Food Science and Nutrition, 57*(15), 3208–3217.

Adebo, O. A., Njobeh, P. B., Sidu, S., Tlou, M. G., & Mavumengwana, V. (2016). Aflatoxin B_1 degradation by liquid cultures and lysates of three bacterial strains. *International Journal of Food Microbiology, 233*, 11–19.

Aiko, V., Edamana, P., & Mehta, A. (2016). Decomposition and detoxification of aflatoxin B_1 by lactic acid. *Journal of the Science of Food and Agriculture, 96*(6), 1959–1966.

Alberts, J. F., Gelderblom, W. C., Botha, A., & van Zyl, W. H. (2009). Degradation of aflatoxin B_1 by fungal laccase enzymes. *International Journal of Food Microbiology, 135*(1), 47–52.

Alkadi, H., & Altal, J. (2019). Effect of microwave oven processing treatments on reduction of aflatoxin B_1 and ochratoxin A in maize flour. *European Journal of Chemistry, 10*(3), 224–227.

Assuncao, E., Reis, T. A., Baquiao, A. C., & Correa, B. (2015). Effects of gamma and electron beam radiation on Brazil nuts artificially inoculated with *Aspergillus flavus*. *Journal of Food Protection, 78*(7), 1397–1401.

Bbosa, G. S., Kitya, D., Odda, J., & Ogwal-Okeng, J. (2013). Aflatoxins metabolism, effects on epigenetic mechanisms and their role in carcinogenesis. *Health, 05*, 14–34.

Benkerroum, N. (2020). Chronic and acute toxicities of aflatoxins: Mechanisms of action. *International Journal of Environmental Research and Public Health, 17*(2).

Blount, W. P. (1961). Turkey "X" disease. *Turkeys, 9*, 52–77.

Boudergue, C., Burel, C., Dragacci, S., Favrot, M. C., Fremy, J. M., Massimi, C., … Avantaggiato, G. (2009). Review of mycotoxin-detoxifying agents used as feed additives: Mode of action, efficacy and feed/food safety. *EFSA Supporting Publications, 6*(9), 22E.

Brana, M. T., Cimmarusti, M. T., Haidukowski, M., Logrieco, A. F., & Altomare, C. (2017). Bioremediation of aflatoxin B_1-contaminated maize by king oyster mushroom (*Pleurotus eryngii*). *PLoS ONE, 12*(8), Article e0182574.

Brinda, R., Vijayanandraj, S., Uma, D., Malathi, D., Paranidharan, V., & Velazhahan, R. (2013). Role of *Adhatoda vasica (L.) Nees* leaf extract in the prevention of aflatoxin-induced toxicity in Wistar rats. *Journal of the Science of Food and Agriculture, 93*(11), 2743–2748.

Cai, S., Han, Q., Qi, C., Lian, Z., Jia, X., Yang, R., & Wang, C. (2016). $Pt_{74}Ag_{26}$ nanoparticle-decorated ultrathin MoS_2 nanosheets as novel peroxidase mimics for highly selective colorimetric detection of H_2O_2 and glucose. *Nanoscale, 8*(6), 3685–3693.

Calado, T., Venâncio, A., & Abrunhosa, L. (2014). Irradiation for mold and mycotoxin control: A review. *Comprehensive Reviews in Food Science and Food Safety, 13*(5), 1049–1061.

Cao, H., Liu, D., Mo, X., Xie, C., & Yao, D. (2011). A fungal enzyme with the ability of aflatoxin B_1 conversion: Purification and ESI-MS/MS identification. *Microbiological Research, 166*(6), 475–483.

Caulfield, C. D., Cassidy, J. P., & Kelly, J. P. (2008). Effects of gamma irradiation and pasteurization on the nutritive composition of commercially available animal diets. *Journal of the American Association for Laboratory Animal Science, 47*(6), 61–66.

Chang, M., Jin, Q., Liu, Y., Liu, R., & Wang, X. (2013). Efficiency and safety evaluation of photodegradation of aflatoxin B_1 on peanut surface. *International Journal of Food Science and Technology, 48*(12), 2474–2479.

Chen, J. G., Egner, P. A., Ng, D., Jacobson, L. P., Munoz, A., Zhu, Y. R., … Kensler, T. W. (2013). Reduced aflatoxin exposure presages decline in liver cancer mortality in an endemic region of China. *Cancer Prevention Research, 6*(10), 1038–1045.

Chen, J. G., & Zhang, S. W. (2011). Liver cancer epidemic in China: Past, present and future. *Seminars in Cancer Biology, 21*(1), 59–69.

Chen, M., Yang, B., Zhu, J., Liu, H., Zhang, X., Zheng, X., & Liu, Q. (2018). FePt nanoparticles-decorated graphene oxide nanosheets as enhanced peroxidase mimics for sensitive response to H_2O_2. *Materials Science & Engineering C-Materials for Biological Applications, 90*, 610–620.

Chen, R., Ma, F., Li, P. W., Zhang, W., Ding, X. X., Zhang, Q., … Xu, B. C. (2014). Effect of ozone on aflatoxins detoxification and nutritional quality of peanuts. *Food Chemistry, 146*, 284–288.

Chen, Y., Chen, T., Wu, X., & Yang, G. (2019). $CuMnO_2$ nanoflakes as pH-switchable catalysts with multiple enzyme-like activities for cysteine detection. *Sensors and Actuators B-Chemical, 279*, 374–384.

Chi, M. Q., Chen, S. H., Zhong, M. X., Wang, C., & Lu, X. F. (2018). Self-templated fabrication of $FeMnO_3$ nanoparticle-filled polypyrrole nanotubes for peroxidase mimicking with a synergistic effect and their sensitive colorimetric detection of glutathione. *Chemical Communications, 54*(46), 5827–5830.

Cserháti, M., Kriszt, B., Krifaton, C., Szoboszlay, S., Háhn, J., Tóth, S., … Kukolya, J. (2013). Mycotoxin-degradation profile of *Rhodococcus* strains. *International Journal of Food Microbiology, 166*(1), 176–185.

Das, A., Bhattacharya, S., Palaniswamy, M., & Angayarkanni, J. (2014). Biodegradation of aflatoxin B_1 in contaminated rice straw by *Pleurotus ostreatus* MTCC 142 and

Pleurotus ostreatus GHBBF10 in the presence of metal salts and surfactants. *World Journal of Microbiology and Biotechnology, 30*(8), 2315–2324.
Das, C., & Mishra, H. N. (2000). In vitro degradation of aflatoxin B_1 by horse radish peroxidase. *Food Chemistry, 68*(3), 309–313.
de Alencar, E. R., Faroni, L. R., Soares Nde, F., da Silva, W. A., & Carvalho, M. C. (2012). Efficacy of ozone as a fungicidal and detoxifying agent of aflatoxins in peanuts. *Journal of the Science of Food and Agriculture, 92*(4), 899–905.
Deckardt, K., Khiaosa-ard, R., Grausgruber, H., & Zebeli, Q. (2014). Evaluation of various chemical and thermal feed processing methods for their potential to enhance resistant starch content in barley grain. *Starch -Starke, 66*(5–6), 558–565.
Delorme, M. M., Guimarães, J. T., Coutinho, N. M., Balthazar, C. F., Rocha, R. S., Silva, R., … Cruz, A. G. (2020). Ultraviolet radiation: An interesting technology to preserve quality and safety of milk and dairy foods. *Trends in Food Science and Technology, 102*, 146–154.
Diao, E., Hou, H., Chen, B., Shan, C., & Dong, H. (2013). Ozonolysis efficiency and safety evaluation of aflatoxin B_1 in peanuts. *Food and Chemical Toxicology, 55*, 519–525.
Diao, E., Hou, H., & Dong, H. (2013). Ozonolysis mechanism and influencing factors of aflatoxin B_1: A review. *Trends in Food Science and Technology, 33*(1), 21–26.
Diao, E., Li, X., Zhang, Z., Ma, W., Ji, N., & Dong, H. (2015). Ultraviolet irradiation detoxification of aflatoxins. *Trends in Food Science and Technology, 42*(1), 64–69.
Diao, E., Shen, X., Zhang, Z., Ji, N., Ma, W., & Dong, H. (2015). Safety evaluation of aflatoxin B_1 in peanut oil after ultraviolet irradiation detoxification in a photodegradation reactor. *International Journal of Food Science & Technology, 50*(1), 41–47.
Di Stefano, V., Pitonzo, R., Cicero, N., & D'Oca, M. C. (2014). Mycotoxin contamination of animal feedingstuff: Detoxification by gamma-irradiation and reduction of aflatoxins and ochratoxin A concentrations. *Food Additives and Contaminants Part A, 31*(12), 2034–2039.
Domijan, A. M., Marjanovic Cermak, A. M., Vulic, A., Tartaro Bujak, I., Pavicic, I., Pleadin, J., … Mihaljevic, B. (2019). Cytotoxicity of gamma irradiated aflatoxin B_1 and ochratoxin A. *Journal of Environmental Science and Health Part B, 54*(3), 155–162.
Dunn, J., Ott, T., & Clark, W. (1995). Pulsed-light treatment of food and packaging. *Food Technology, 49*(9), 95–98.
EC. 2010. Commission Regulation (EU) No 165/2010 of 26 February 2010 amending Regulation (EC) No 1881/2006 setting maximum levels for certain contaminants in foodstuffs as regards aflatoxins. Official Journal of European Union, L50/8–L50/12.
EFSA. (2007). Scientific opinion related to the potential increase of consumer health risk by a possible increase of the existing maximum levels for aflatoxins in almonds, hazelnuts and pistachios and derived products. *European Food Safety Authority. EFSA Journal, 5*(446), 127.
Elaasser, M., & El Kassas, R. (2011). Detoxification of aflatoxin B_1 by certain bacterial species isolated from Egyptian soil. *World Mycotoxin Journal, 4*(2), 169–176.
El-Deeb, B., Altalhi, A., Khiralla, G., Hassan, S., & Gherbawy, Y. (2013). Isolation and characterization of endophytic *Bacilli* bacterium from maize grains able to detoxify aflatoxin B_1. *Food Biotechnology, 27*(3), 199–212.
Elliott, C. T., Connolly, L., & Kolawole, O. (2019). Potential adverse effects on animal health and performance caused by the addition of mineral adsorbents to feeds to reduce mycotoxin exposure. *Mycotoxin Research, 36*(1), 115–126.
Escobedo-Gonzalez, R., Mendez-Albores, A., Villarreal-Barajas, T., Aceves-Hernandez, J. M., Miranda-Ruvalcaba, R., & Nicolas-Vazquez, I. (2016). A theoretical study of 8-chloro-9-hydroxy-aflatoxin B_1, the conversion product of aflatoxin B_1 by neutral electrolyzed water. *Toxins, 8*(7), 225.
Eshelli, M., Harvey, L., Edrada-Ebel, R., & McNeil, B. (2015). Metabolomics of the biodegradation process of aflatoxin B_1 by *Actinomycetes* at an initial pH of 6.0. *Toxins, 7*(2), 439–456.
Fan, S., Zhang, F., Liu, S., Yu, C., Guan, D., & Pan, C. (2013). Removal of aflatoxin B_1 in edible plant oils by oscillating treatment with alkaline electrolysed water. *Food Chemistry, 141*(3), 3118–3123.
Fan, X., Huang, R., & Chen, H. (2017). Application of ultraviolet C technology for surface decontamination of fresh produce. *Trends in Food Science and Technology, 70*, 9–19.
Fan, Y., Liu, L., Zhao, L., Wang, X., Wang, D., Huang, C., … Ma, Q. (2018). Influence of *Bacillus subtilis* ANSB060 on growth, digestive enzyme and aflatoxin residue in Yellow River carp fed diets contaminated with aflatoxin B_1. *Food and Chemical Toxicology, 113*, 108–114.
Fan, Y., Zhao, L., Ji, C., Li, X., Jia, R., Xi, L., … Ma, Q. (2015). Protective effects of *Bacillus subtilis* ANSB060 on serum biochemistry, histopathological changes and antioxidant enzyme activities of broilers fed moldy peanut meal naturally contaminated with aflatoxins. *Toxins, 7*(8), 3330–3343.
Farzaneh, M., Shi, Z.-Q., Ghassempour, A., Sedaghat, N., Ahmadzadeh, M., Mirabolfathy, M., & Javan-Nikkhah, M. (2012). Aflatoxin B_1 degradation by *Bacillus subtilis* UTBSP1 isolated from pistachio nuts of Iran. *Food Control, 23*(1), 100–106.
FDA. (1996). Code of federal regulations (Title 21, Vol. 3), 21CFR179.41. Silver Spring, MD: United States Government Printing.
FDA. (1982). GRAS status of ozone. *Federal Register, 47*(215), 50209–50210.
FDA. (2001). Secondary direct food additives permitted in food for human consumption. *Federal Register, 66*(123), 33829–33830.
FDA. (2011). *Mycotoxin regulatory guidance* (pp. 1–9). National Grain and Feed Association: Washington, DC, USA.
Figueiredo, A. C., Barroso, J. G., Pedro, L. G., & Scheffer, J. J. C. (2008). Factors affecting secondary metabolite production in plants: Volatile components and essential oils. *Flavour and Fragrance Journal, 23*(4), 213–226.
Fridman, A., Chirokov, A., & Gutsol, A. (2005). Non-thermal atmospheric pressure discharges. *Journal of Physics D-Applied Physics, 38*(2), R1–R24.
Gao, L., Zhuang, J., Nie, L., Zhang, J., Zhang, Y., Gu, N., … Yan, X. (2007). Intrinsic peroxidase-like activity of ferromagnetic nanoparticles. *Nature Nanotechnology, 2*(9), 577–583.
Gao, X., Ma, Q., Zhao, L., Lei, Y., Shan, Y., & Ji, C. (2011). Isolation of *Bacillus subtilis*: Screening for aflatoxins B_1, M_1, and G_1 detoxification. *European Food Research and Technology, 232*(6), 957–962.
Garg, N., Aggarwal, M., Javed, S., & Khandal, R. K. (2013). Studies for optimization of conditions for reducing aflatoxin contamination in peanuts using ultraviolet radiations. *International Journal of Drug Development and Research, 5*(3), 408–424.
Gavahian, M., & Cullen, P. J. (2019). Cold plasma as an emerging technique for mycotoxin-free food: Efficacy, mechanisms, and trends. *Food Reviews International, 36*(2), 1–22.
Gayán, E., Condón, S., & Álvarez, I. (2014). Biological aspects in food preservation by ultraviolet light: A review. *Food and Bioprocess Technology, 7*(1), 1–20.
Ghanghro, A. B., Nizamani, M., Channa, M. J., Ghanghro, I. H., & Sheikh, S. A. (2016). Assessment of aflatoxin level in stored wheat of godowns of hyderabad division and decontamination by UV radiation. *International Journal of Biosciences, 8*(1), 8–16.
Gomez-Espinosa, D., Cervantes-Aguilar, F. J., Del Rio-Garcia, J. C., Villarreal-Barajas, T., Vazquez-Duran, A., & Mendez-Albores, A. (2017). Ameliorative effects of neutral electrolyzed water on growth performance, biochemical constituents, and histopathological changes in turkey poults during aflatoxicosis. *Toxins, 9*(3), 104.
Gonzalez Pereyra, M. L., Martinez, M. P., & Cavaglieri, L. R. (2019). Presence of aiiA homologue genes encoding for N-Acyl homoserine lactone-degrading enzyme in aflatoxin B_1-decontaminating *Bacillus* strains with potential use as feed additives. *Food and Chemical Toxicology, 124*, 316–323.
Guan, L. Z., Sun, Y. P., Cai, J. S., Wu, H. D., Yu, L. Z., Zhang, Y. L., & Xi, Q. Y. (2015). The aflatoxin-detoxifizyme specific expression in mouse parotid gland. *Transgenic Research, 24*(3), 489–496.
Guan, Z. B., Luo, Q., Wang, H. R., Chen, Y., & Liao, X. R. (2018). Bacterial laccases: Promising biological green tools for industrial applications. *Cellular and Molecular Life Sciences, 75*(19), 3569–3592.
Guo, Y., Qin, X., Tang, Y., Ma, Q., Zhang, J., & Zhao, L. (2020). CotA laccase, a novel aflatoxin oxidase from *Bacillus licheniformis*, transforms aflatoxin B_1 to aflatoxin Q_1 and epi-aflatoxin Q_1. *Food Chemistry, 325*, Article 126877.
Guo, Y., Zhang, Y., Wei, C., Ma, Q., Ji, C., Zhang, J., & Zhao, L. (2019). Efficacy of *Bacillus subtilis* ANSB060 biodegradation product for the reduction of the milk aflatoxin M_1 content of dairy cows exposed to aflatoxin B_1. *Toxins, 11*(3), 161.
Harkai, P., Szabó, I., Cserháti, M., Krifaton, C., Risa, A., Radó, J., … Kriszt, B. (2016). Biodegradation of aflatoxin-B_1 and zearalenone by *Streptomyces* sp. collection. *International Biodeterioration and Biodegradation, 108*, 48–56.
Hertwig, C., Meneses, N., & Mathys, A. (2018). Cold atmospheric pressure plasma and low energy electron beam as alternative nonthermal decontamination technologies for dry food surfaces: A review. *Trends in Food Science and Technology, 77*, 131–142.
Hou, C., Wang, Y., Ding, Q., Jiang, L., Li, M., Zhu, W., … Liu, M. (2015). Facile synthesis of enzyme-embedded magnetic metal-organic frameworks as a reusable mimic multi-enzyme system: Mimetic peroxidase properties and colorimetric sensor. *Nanoscale, 7*(44), 18770–18779.
Huang, Y.-R., Hung, Y.-C., Hsu, S.-Y., Huang, Y.-W., & Hwang, D.-F. (2008). Application of electrolyzed water in the food industry. *Food Control, 19*(4), 329–345.
Iqbal, Q., Amjad, M., Asi, M. R., & Arino, A. (2012). Mold and aflatoxin reduction by gamma radiation of packed hot peppers and their evolution during storage. *Journal of Food Protection, 75*(8), 1528–1531.
Iqbal, S. Z., Bhatti, I. A., Asi, M. R., Zuber, M., Shahid, M., & Parveen, I. (2013). Effect of γ irradiation on fungal load and aflatoxins reduction in red chillies. *Radiation Physics and Chemistry, 82*(1), 80–84.
Iqdiam, B. M., Abuagela, M. O., Boz, Z., Marshall, S. M., Goodrich-Schneider, R., Sims, C. A., … Welt, B. A. (2019). Effects of atmospheric pressure plasma jet treatment on aflatoxin level, physiochemical quality, and sensory attributes of peanuts. *Journal of Food Processing and Preservation, 44*(1), Article e14305.
Iram, W., Anjum, T., Iqbal, M., Ghaffar, A., & Abbas, M. (2015). Mass spectrometric identification and toxicity assessment of degraded products of aflatoxin B_1 and B_2 by *Corymbia citriodora* aqueous extracts. *Scientific Reports, 5*(1), 14672.
Iram, W., Anjum, T., Iqbal, M., Ghaffar, A., & Abbas, M. (2016). Structural elucidation and toxicity assessment of degraded products of aflatoxin B_1 and B_2 by aqueous extracts of *Trachyspermum ammi*. *Frontiers in Microbiology, 7*, 346.
Iram, W., Anjum, T., Iqbal, M., Ghaffar, A., Abbas, M., & Khan, A. M. (2016). Structural analysis and biological toxicity of aflatoxins B_1 and B_2 degradation products following detoxification by *Ocimum basilicum* and *Cassia fistula* aqueous extracts. *Frontiers in Microbiology, 7*, 1105.
Ismail, A., Goncalves, B. L., de Neeff, D. V., Ponzilacqua, B., Coppa, C., Hintzsche, H., … Oliveira, C. A. F. (2018). Aflatoxin in foodstuffs: Occurrence and recent advances in decontamination. *Food Research International, 113*, 74–85.
Jackson, L. W., 3rd, & Pryor, B. M. (2017). Degradation of aflatoxin B_1 from naturally contaminated maize using the edible fungus *Pleurotus ostreatus*. *AMB Expression, 7*(1), 110.
Jalili, M. (2016). A review on aflatoxins reduction in food. *Iranian Journal of Health, Safety and Environment, 3*(1), 445–459.
Jalili, M., Jinap, S., & Noranizan, M. A. (2012). Aflatoxins and ochratoxin A reduction in black and white pepper by gamma radiation. *Radiation Physics and Chemistry, 81*(11), 1786–1788.
Jalili, M., Jinap, S., & Son, R. (2011). The effect of chemical treatment on reduction of aflatoxins and ochratoxin A in black and white pepper during washing. *Food Additives and Contaminants Part A, 28*(4), 485–493.
Jamil, T. S., Abbas, H. A., Nasr, R. A., El-Kady, A. A., & Ibrahim, M. I. M. (2017). Detoxification of aflatoxin B_1 using nano-sized Sc-doped $SrTi_{0.7}Fe_{0.3}O_3$ under visible light. *Journal of Photochemistry and Photobiology A: Chemistry, 341*, 127–135.
Jard, G., Liboz, T., Mathieu, F., Guyonvarc'h, A., & Lebrihi, A. (2011). Review of mycotoxin reduction in food and feed: From prevention in the field to detoxification

by adsorption or transformation. *Food Additives and Contaminants Part A, 28*(11), 1590–1609.
Jardon-Xicotencatl, S., Diaz-Torres, R., Marroquin-Cardona, A., Villarreal-Barajas, T., & Mendez-Albores, A. (2015). Detoxification of aflatoxin-contaminated maize by neutral electrolyzed oxidizing water. *Toxins, 7*(10), 4294–4314.
Ji, C., Fan, Y., & Zhao, L. (2016). Review on biological degradation of mycotoxins. *Animal Nutrition, 2*(3), 127–133.
Jr., A. D. P., & King, J. M. (2002). Efficacy and safety evaluation of ozonation to degrade aflatoxin in corn. Journal of Food Science, 67 (8), 2866-2872.
Kabak, B. (2009). The fate of mycotoxins during thermal food processing. *Journal of the Science of Food and Agriculture, 89*(4), 549–554.
Kamber, U., Gülbaz, G., Aksu, P., & Doğan, A. (2017). Detoxification of aflatoxin B_1 in red pepper (*Capsicum annuum L.*) by ozone treatment and its effect on microbiological and sensory quality. *Journal of Food Processing and Preservation, 41*(5), Article e13102.
Karlovsky, P., Suman, M., Berthiller, F., De Meester, J., Eisenbrand, G., Perrin, I., … Dussort, P. (2016). Impact of food processing and detoxification treatments on mycotoxin contamination. *Mycotoxin Research, 32*(4), 179–205.
Kogelschatz, U. (2004). Atmospheric-pressure plasma technology. *Plasma Physics and Controlled Fusion, 46*(12B), B63–B75.
Kong, Q., Zhai, C., Guan, B., Li, C., Shan, S., & Yu, J. (2012). Mathematic modeling for optimum conditions on aflatoxin B_1 degradation by the aerobic bacterium *Rhodococcus erythropolis*. *Toxins, 4*(11), 1181–1195.
Krifaton, C., Kriszt, B., Szoboszlay, S., Cserháti, M., Szűcs, Á., & Kukolya, J. (2011). Analysis of aflatoxin-B_1-degrading microbes by use of a combined toxicity-profiling method. *Mutation Research-Genetic Toxicology and Environmental Mutagenesis, 726*(1), 1–7.
Kumar, P., Mahato, D. K., Kamle, M., Mohanta, T. K., & Kang, S. G. (2016). Aflatoxins: A global concern for food safety, human health and their management. *Frontiers in Microbiology, 7*, 2170.
Lapalikar, G. V., Taylor, M. C., Warden, A. C., Scott, C., Russell, R. J., & Oakeshott, J. G. (2012). $F_{420}H_2$-dependent degradation of aflatoxin and other furanocoumarins is widespread throughout the *Actinomycetales*. *PLoS ONE, 7*(2), Article e30114.
Lee, J., Her, J. Y., & Lee, K. G. (2015). Reduction of aflatoxins (B_1, B_2, G_1, and G_2) in soybean-based model systems. *Food Chemistry, 189*(SI), 45–51.
Li, C. H., Li, W. Y., Hsu, I. N., Liao, Y. Y., Yang, C. Y., Taylor, M. C., … Tsai, R. T. (2019). Recombinant aflatoxin-degrading $F_{420}H_2$-dependent reductase from *Mycobacterium smegmatis* protects mammalian cells from aflatoxin toxicity. *Toxins, 11*(5), 259.
Liang, H., Lin, F., Zhang, Z., Liu, B., Jiang, S., Yuan, Q., & Liu, J. (2017). Multicopper laccase mimicking nanozymes with nucleotides as ligands. *ACS Applied Materials and Interfaces, 9*(2), 1352–1360.
Liu, D., Yao, D., Liang, R., Ma, L., Cheng, W., & Gu, L. (1998). Detoxifcation of aflatoxin B_1 by enzymes isolated from *Armillariella tabescens*. *Food and Chemical Toxicology, 36*(7), 563–574.
Liu, D. L., Yao, D. S., Liang, Y. Q., Zhou, T. H., Song, Y. P., Zhao, L., & Ma, L. (2001). Production, purification, and characterization of an intracellular aflatoxin-detoxifizyme from *Armillariella tabescens* (E-20). *Food and Chemical Toxicology, 39*(5), 461–466.
Liu, R., Jin, Q., Huang, J., Liu, Y., Wang, X., Mao, W., & Wang, S. (2011). Photodegradation of aflatoxin B_1 in peanut oil. *European Food Research and Technology, 232*(5), 843–849.
Liu, R., Jin, Q., Tao, G., Shan, L., Huang, J., Liu, Y., … Wang, S. (2010). Photodegradation kinetics and byproducts identification of the aflatoxin B_1 in aqueous medium by ultra-performance liquid chromatography-quadrupole time-of-flight mass spectrometry. *Journal of Mass Spectrometry, 45*(5), 553–559.
Liu, R., Lu, M., Wang, R., Wang, S., Chang, M., Jin, Q., & Wang, X. (2018). Degradation of aflatoxin B_1 in peanut meal by electron beam irradiation. *International Journal of Food Properties, 21*(1), 892–901.
Liu, R., Wang, R., Lu, J., Chang, M., Jin, Q., Du, Z., … Wang, X. (2016). Degradation of AFB_1 in aqueous medium by electron beam irradiation: Kinetics, pathway and toxicology. *Food Control, 66*, 151–157.
Liu, Y., & Wu, F. (2010). Estimating the global burden of aflatoxin-attributed hepatocellular carcinoma - A risk assessment. *Environmental Health Perspectives, 118*(6), 818–824.
Loi, M., Fanelli, F., Cimmarusti, M. T., Mirabelli, V., Haidukowski, M., Logrieco, A. F., … Mule, G. (2018). In vitro single and combined mycotoxins degradation by Ery4 laccase from *Pleurotus eryngii* and redox mediators. *Food Control, 90*, 401–406.
Loi, M., Fanelli, F., Zucca, P., Liuzzi, V. C., Quintieri, L., Cimmarusti, M. T., … Mule, G. (2016). Aflatoxin B_1 and M_1 degradation by Lac2 from *Pleurotus pulmonarius* and redox mediators. *Toxins, 8*(9), 245.
Loi, M., Paciolla, C., Logrieco, A. F., & Mulè, G. (2020). *Plant bioactive compounds in pre- and postharvest management for aflatoxins reduction* (p. 11). Frontiers in Microbiology.
Loi, M., Renaud, J. B., Rosini, E., Pollegioni, L., Vignali, E., Haidukowski, M., … Mulè, G. (2020). Enzymatic transformation of aflatoxin B_1 by Rh_DypB peroxidase and characterization of the reaction products. *Chemosphere, 250*, Article 126296.
Lou, A. G., Cai, J. S., Zhang, X. M., Cui, C. D., Piao, Y. S., & Guan, L. Z. (2017). The aflatoxin-detoxifizyme specific expression in the parotid gland of transgenic pigs. *Transgenic Research, 26*(5), 677–687.
Luo, X., Wang, R., Wang, L., Li, Y., Bian, Y., & Chen, Z. (2014). Effect of ozone treatment on aflatoxin B_1 and safety evaluation of ozonized corn. *Food Control, 37*, 171–176.
Luo, X., Wang, R., Wang, L., Li, Y., Wang, Y., & Chen, Z. (2014). Detoxification of aflatoxin in corn flour by ozone. *Journal of the Science of Food and Agriculture, 94*(11), 2253–2258.
Luo, Y., Liu, X., Yuan, L., & Li, J. (2020). Complicated interactions between bio-adsorbents and mycotoxins during mycotoxin adsorption: Current research and future prospects. *Trends in Food Science and Technology, 96*, 127–134.
Magzoub, R. A. M., Yassin, A. A. A., Abdel-Rahim, A. M., Gubartallah, E. A., Miskam, M., Saad, B., & Sabar, S. (2019). Photocatalytic detoxification of aflatoxins in Sudanese peanut oil using immobilized titanium dioxide. *Food Control, 95*, 206–214.
Ma, Q. G., Gao, X., Zhou, T., Zhao, L. H., Fan, Y., Li, X. Y., … Zhang, J. Y. (2012). Protective effect of *Bacillus subtilis* ANSB060 on egg quality, biochemical and histopathological changes in layers exposed to aflatoxin B_1. *Poultry Science, 91*(11), 2852–2857.
Ma, R., Zhang, L., Liu, M., Su, Y. T., Xie, W. M., Zhang, N. Y., … Sun, L. H. (2018). Individual and combined occurrence of mycotoxins in feed ingredients and complete feeds in China. *Toxins, 10*(3), 113.
Mao, J., He, B., Zhang, L., Li, P., Zhang, Q., Ding, X., & Zhang, W. (2016). A structure identification and toxicity assessment of the degradation products of aflatoxin B_1 in peanut oil under UV irradiation. *Toxins, 8*(11), 332.
Mao, J., Li, P., Wang, J., Wang, H., Zhang, Q., Zhang, L., … Peng, T. (2019). Insights into photocatalytic inactivation mechanism of the hypertoxic site in aflatoxin B_1 over clew-like WO_3 decorated with CdS nanoparticles. *Applied Catalysis B-Environmental, 248*, 477–486.
Mao, J., Zhang, L., Wang, H., Zhang, Q., Zhang, W., & Li, P. (2018). Facile fabrication of nanosized graphitic carbon nitride sheets with efficient charge separation for mitigation of toxic pollutant. *Chemical Engineering Journal, 342*, 30–40.
Marchese, S., Polo, A., Ariano, A., Velotto, S., Costantini, S., & Severino, L. (2018). Aflatoxin B_1 and M_1: Biological properties and their involvement in cancer development. *Toxins, 10*, 214.
Marimón Sibaja, K. V., de Oliveira Garcia, S., Feltrin, A. C. P., Diaz Remedi, R., Cerqueira, M. B. R., Badiale-Furlong, E., & Garda-Buffon, J. (2018). Aflatoxin biotransformation by commercial peroxidase and its application in contaminated food. *Journal of Chemical Technology and Biotechnology, 94*(4), 1187–1194.
Markov, K., Mihaljević, B., Domijan, A.-M., Pleadin, J., Delaš, F., & Frece, J. (2015). Inactivation of aflatoxigenic fungi and the reduction of aflatoxin B_1 in vitro and in situ using gamma irradiation. *Food Control, 54*, 79–85.
Méndez-Albores, A., Veles-Medina, J., Urbina-Álvarez, E., Martínez-Bustos, F., & Moreno-Martínez, E. (2009). Effect of citric acid on aflatoxin degradation and on functional and textural properties of extruded sorghum. *Animal Feed Science and Technology, 150*(3–4), 316–329.
Menon, A., Stojceska, V., & Tassou, S. A. (2020). A systematic review on the recent advances of the energy efficiency improvements in non-conventional food drying technologies. *Trends in Food Science and Technology, 100*, 67–76.
Metzler-Zebeli, B. U., Deckardt, K., Schollenberger, M., Rodehutscord, M., & Zebeli, Q. (2014). Lactic acid and thermal treatments trigger the hydrolysis of myo-inositol hexakisphosphate and modify the abundance of lower myo-inositol phosphates in barley (Hordeum vulgare L.). *PLoS ONE, 9*(6), Article e101166.
Misra, N. N., Yadav, B., Roopesh, M. S., & Jo, C. (2019). Cold plasma for effective fungal and mycotoxin control in foods: Mechanisms, inactivation effects, and applications. *Comprehensive Reviews in Food Science and Food Safety, 18*(1), 106–120.
Mobeen, A. K., Aftab, A., Asif, A., & Zuzzer, A. S. (2011). Aflatoxins B_1 and B_2 contamination of peanut and peanut products and subsequent microwave detoxification. *Journal of Pharmacy and Nutrition Sciences, 1*(1), 1–3.
Mohamed, N. F., El-Dine, R. S. S., Kotb, M. A. M., & Saber, A. (2015). Assessing the possible effect of gamma irradiation on the reduction of aflatoxin B_1, and on the moisture content in some cereal grains. *American Journal of Biomedical Sciences, 7*(1), 33–39.
Moreau, M., Lescure, G., Agoulon, A., Svinareff, P., Orange, N., & Feuilloley, M. (2013). Application of the pulsed light technology to mycotoxin degradation and inactivation. *Journal of Applied Toxicology, 33*(5), 357–363.
My, A., & Sachan, D. (1997). Dietary factors affecting aflatoxin Bi carcinogenicity. *Malaysian Journal of Nutritio, n, 3*, 161–179.
Negera, M., & Washe, A. P. (2019). Use of natural dietary spices for reclamation of food quality impairment by aflatoxin. *Journal of Food Quality, 2019*, 4371206.
Oms-Oliu, G., Martín-Belloso, O., & Soliva-Fortuny, R. (2010). Pulsed light treatments for food preservation. *A review. Food and Bioprocess Technology, 3*(1), 13–23.
Ostry, V., Malir, F., Toman, J., & Grosse, Y. (2017). Mycotoxins as human carcinogens-the IARC Monographs classification. *Mycotoxin Research, 33*(1), 65–73.
Pal, P., Kaur, P., Singh, N., Kaur, A., Misra, N. N., Tiwari, B. K., … Virdi, A. S. (2016). Effect of nonthermal plasma on physico-chemical, amino acid composition, pasting and protein characteristics of short and long grain rice flour. *Food Research International, 81*, 50–57.
Panda, P., & Mehta, A. (2013). Aflatoxin detoxification potential of *ocimum tenuiflorum*. *Journal of Food Safety, 33*(3), 265–272.
Pandey, M. K., Kumar, R., Pandey, A. K., Soni, P., Gangurde, S. S., Sudini, H. K., … Varshney, R. K. (2019). Mitigating aflatoxin contamination in groundnut through a combination of genetic resistance and post-harvest management practices. *Toxins, 11*(6), 135.
Pandiselvam, R., Subhashini, S., Banuu Priya, E. P., Kothakota, A., Ramesh, S. V., & Shahir, S. (2018). Ozone based food preservation: A promising green technology for enhanced food safety. *Ozone-Science & Engineering, 41*(1), 17–34.
Patil, H., Shah, N. G., Hajare, S. N., Gautam, S., & Kumar, G. (2019). Combination of microwave and gamma irradiation for reduction of aflatoxin B_1 and microbiological contamination in peanuts (*Arachis hypogaea L.*). *World Mycotoxin Journal, 12*(3), 269–280.
Pérez-Flores, G. C., Moreno-Martínez, E., & Méndez-Albores, A. (2011). Effect of microwave heating during alkaline-cooking of aflatoxin contaminated maize. *Journal of Food Science, 76*(2), T48–T52.
Ponzilacqua, B., Rottinghaus, G. E., Landers, B. R., & Oliveira, C. A. F. (2019). Effects of medicinal herb and Brazilian traditional plant extracts on in vitro mycotoxin decontamination. *Food Control, 100*, 24–27.

Prettl, Z., Dési, E., Lepossa, A., Kriszt, B., Kukolya, J., & Nagy, E. (2017). Biological degradation of aflatoxin B_1 by a *Rhodococcus pyridinivorans* strain in by-product of bioethanol. *Animal Feed Science and Technology, 224*, 104–114.

Priyadarshini, A., Rajauria, G., O'Donnell, C. P., & Tiwari, B. K. (2019). Emerging food processing technologies and factors impacting their industrial adoption. *Critical Reviews in Food Science and Nutrition, 59*(19), 3082–3101.

Puligundla, P., Lee, T., & Mok, C. (2019). Effect of corona discharge plasma jet treatment on the degradation of aflatoxin B_1 on glass slides and in spiked food commodities. *Lwt-Food Science and Technology, 124*, Article 108333.

Rahman, S. M. E., Khan, I., & Oh, D.-H. (2016). Electrolyzed water as a novel sanitizer in the food industry: Current trends and future perspectives. *Comprehensive Reviews in Food Science and Food Safety, 15*(3), 471–490.

Raksha Rao, K., Vipin, A. V., Hariprasad, P., Anu Appaiah, K. A., & Venkateswaran, G. (2017). Biological detoxification of aflatoxin B_1 by *Bacillus licheniformis* CFR1. *Food Control, 71*, 234–241.

Rastegar, H., Shoeibi, S., Yazdanpanah, H., Amirahmadi, M., Khaneghah, A. M., Campagnollo, F. B., & S. Sant'Ana, A. (2017). Removal of aflatoxin B1 by roasting with lemon juice and/or citric acid in contaminated pistachio nuts. Food Control, 71, 279-284.

Reddy, K. R. N., Salleh, B., Saad, B., Abbas, H. K., Abel, C. A., & Shier, W. T. (2010). An overview of mycotoxin contamination in foods and its implications for human health. *Toxin Reviews, 29*(1), 3–26.

Ren, Z., Luo, J., & Wan, Y. (2019). Enzyme-like metal-organic frameworks in polymeric membranes for efficient removal of aflatoxin B_1. *ACS Applied Materials and Interfaces, 11*(34), 30542–30550.

Risa, A., Krifaton, C., Kukolya, J., Kriszt, B., Cserhati, M., & Tancsics, A. (2018). Aflatoxin B_1 and zearalenone-detoxifying profile of *Rhodococcus* type strains. *Current Microbiology, 75*(7), 907–917.

Rushing, B. R., & Selim, M. I. (2016). Effect of dietary acids on the formation of aflatoxin B_{2a} as a means to detoxify aflatoxin B_1. *Food Additives and Contaminants Part A, 33*(9), 1456–1467.

Rushing, B. R., & Selim, M. I. (2019). Aflatoxin B_1: A review on metabolism, toxicity, occurrence in food, occupational exposure, and detoxification methods. *Food And Chemical Toxicology, 124*, 81–100.

Rustom, I. Y. S. (1997). Aflatoxin in food and feed: Occurrence, legislation and inactivation by physical methods. *Food Chemistry, 59*(1), 57–67.

Safara, M., Zaini, F., Hashemi, S., Mahmoudi, M., Khosravi, A., & Shojai-Aliabadi, F. (2010). Aflatoxin detoxification in rice using citric acid. *Iranian Journal of Public Health, 39*(2), 24–29.

Sakudo, A., Toyokawa, Y., Misawa, T., & Imanishi, Y. (2017). Degradation and detoxification of aflatoxin B_1 using nitrogen gas plasma generated by a static induction thyristor as a pulsed power supply. *Food Control, 73*, 619–626.

Samarajeewa, U., Sen, A. C., Cohen, M. D., & Wei, C. I. (1990). Detoxification of aflatoxins in foods and feeds by physical and chemical methods. *Journal of Food Protection, 53*(6), 489–501.

Samuel, M. S., Sivaramakrishna, A., & Mehta, A. (2014). Degradation and detoxification of aflatoxin B_1 by *Pseudomonas putida*. *International Biodeterioration and Biodegradation, 86*, 202–209.

Sangare, L., Zhao, Y., Folly, Y. M., Chang, J., Li, J., Selvaraj, J. N., … Liu, Y. (2014). Aflatoxin B_1 degradation by a *Pseudomonas* strain. *Toxins, 6*(10), 3028–3040.

Savi, G. D., Piacentini, K. C., & Scussel, V. M. (2015). Ozone treatment efficiency in *Aspergillus* and *Penicillium* growth inhibition and mycotoxin degradation of stored wheat grains (*Triticum aestivum* L.). *Journal of Food Processing and Preservation, 39*(6), 940–948.

Shi, H., Cooper, B., Stroshine, R. L., Ileleji, K. E., & Keener, K. M. (2017). Structures of degradation products and degradation pathways of aflatoxin B_1 by high-voltage atmospheric cold plasma (HVACP) treatment. *Journal of Agricultural and Food Chemistry, 65*(30), 6222–6230.

Shi, H., Ileleji, K., Stroshine, R. L., Keener, K., & Jensen, J. L. (2017). Reduction of aflatoxin in corn by high voltage atmospheric cold plasma. *Food and Bioprocess Technology, 10*(6), 1042–1052.

Shu, X., Wang, Y., Zhou, Q., Li, M., Hu, H., Ma, Y., … Wu, L. (2018). Biological degradation of aflatoxin B_1 by cell-free extracts of *Bacillus velezensis* DY3108 with broad pH stability and excellent thermostability. *Toxins, 10*(8), 330.

Siciliano, I., Spadaro, D., Prelle, A., Vallauri, D., Cavallero, M. C., Garibaldi, A., & Gullino, M. L. (2016). Use of cold atmospheric plasma to detoxify hazelnuts from aflatoxins. *Toxins, 8*(5), 125.

Soni, A., Smith, J., Thompson, A., & Brightwell, G. (2020). Microwave-induced thermal sterilization-A review on history, technical progress, advantages and challenges as compared to the conventional methods. *Trends in Food Science and Technology, 97*, 433–442.

Sun, S., Zhao, R., Xie, Y., & Liu, Y. (2019). Photocatalytic degradation of aflatoxin B_1 by activated carbon supported TiO_2 catalyst. *Food Control, 100*, 183–188.

Sun, X., Sun, C., Zhang, X., Zhang, H., Ji, J., Liu, Y., & Tang, L. (2016). Aflatoxin B_1 decontamination by UV-mutated live and immobilized *Aspergillus niger*. *Food Control, 61*, 235–242.

Taylor, M. C., Jackson, C. J., Tattersall, D. B., French, N., Peat, T. S., Newman, J., … Oakeshott, J. G. (2010). Identification and characterization of two families of F420H2-dependent reductases from *Mycobacteria* that catalyse aflatoxin degradation. *Molecular Microbiology, 78*(3), 561–575.

Tiwari, B. K., Brennan, C. S., Curran, T., Gallagher, E., Cullen, P. J., & O' Donnell, C. P. (2010). Application of ozone in grain processing. Journal of Cereal Science, 51 (3), 248-255.

Torlak, E., Akata, I., Erci, F., & Uncu, A. T. (2016). Use of gaseous ozone to reduce aflatoxin B_1 and microorganisms in poultry feed. *Journal of Stored Products Research, 68*, 44–49.

Tripathi, S., & Mishra, H. N. (2009). Modeling and optimization of enzymatic degradation of aflatoxin B_1 (AFB_1) in red chili powder using response surface methodology. *Food and Bioprocess Technology, 4*(5), 770–780.

Tripathi, S., & Mishra, H. N. (2010). Enzymatic coupled with UV degradation of aflatoxin B_1 in red chili powder. *Journal of Food Quality, 33*, 186–203.

Trombete, F. M., Porto, Y. D., Freitas-Silva, O., Pereira, R. V., Direito, G. M., Saldanha, T., & Fraga, M. E. (2017). Efficacy of ozone treatment on mycotoxins and fungal reduction in artificially contaminated soft wheat grains. *Journal of Food Processing and Preservation, 41*(3), Article e12927.

Udomkun, P., Wiredu, A. N., Nagle, M., Muller, J., Vanlauwe, B., & Bandyopadhyay, R. (2017). Innovative technologies to manage aflatoxins in foods and feeds and the profitability of application - A review. *Food Control, 76*, 127–138.

Umesha, S., Manukumar, H. M., Chandrasekhar, B., Shivakumara, P., Shiva Kumar, J., Raghava, S., … Prakash, H. S. (2017). Aflatoxins and food pathogens: Impact of biologically active aflatoxins and their control strategies. *Journal of the Science of Food and Agriculture, 97*(6), 1698–1707.

Vekiru, E., Fruhauf, S., Rodrigues, I., Ottner, F., Krska, R., Schatzmayr, G., … Bermudez, A. J. (2015). In vitro binding assessment and in vivo efficacy of several adsorbents against aflatoxin B_1. *World Mycotoxin Journal, 8*(4), 477–488.

Velazhahan, R., Vijayanandraj, S., Vijayasamundeeswari, A., Paranidharan, V., Samiyappan, R., Iwamoto, T., … Muthukrishnan, S. (2010). Detoxification of aflatoxins by seed extracts of the medicinal plant, *Trachyspermum ammi* (L.) Sprague ex Turrill-Structural analysis and biological toxicity of degradation product of aflatoxin G1. *Food Control, 21*(5), 719–725.

Vijayanandraj, S., Brinda, R., Kannan, K., Adhithya, R., Vinothini, S., Senthil, K., … Velazhahan, R. (2014). Detoxification of aflatoxin B_1 by an aqueous extract from leaves of *Adhatoda vasica Nees*. *Microbiological Research, 169*(4), 294–300.

Vita, D. S., Rosa, P., & Giuseppe, A. (2014). Effect of gamma irradiation on aflatoxins and ochratoxin A reduction in almond samples. *Journal of Food Research, 3*(4), 113–118.

Vötterl, J. C., Zebeli, Q., Hennig-Pauka, I., & Metzler-Zebeli, B. U. (2019). Soaking in lactic acid lowers the phytate-phosphorus content and increases the resistant starch in wheat and corn grains. *Animal Feed Science and Technology, 252*, 115–125.

Wang, B., Mahoney, N. E., Pan, Z., Khir, R., Wu, B., Ma, H., & Zhao, L. (2016). Effectiveness of pulsed light treatment for degradation and detoxification of aflatoxin B_1 and B_2 in rough rice and rice bran. *Food Control, 59*, 461–467.

Wang, F., Xie, F., Xue, X., Wang, Z., Fan, B., & Ha, Y. (2011). Structure elucidation and toxicity analyses of the radiolytic products of aflatoxin B_1 in methanol-water solution. *Journal of Hazardous Materials, 192*(3), 1192–1202.

Wang, J., Ogata, M., Hirai, H., & Kawagishi, H. (2011). Detoxification of aflatoxin B_1 by manganese peroxidase from the white-rot fungus *Phanerochaete sordida* YK-624. *FEMS Microbiology Letters, 314*(2), 164–169.

Wang, L., Wu, J., Liu, Z., Shi, Y., Liu, J., Xu, X., … Deng, Y. (2018). Aflatoxin B_1 degradation and detoxification by *Escherichia coli* CG1061 isolated from chicken cecum. *Frontiers in Pharmacology, 9*, 1548.

Wang, R., Liu, R., Chang, M., Jin, Q., Huang, J., Liu, Y., & Wang, X. (2015). Ultra-performance liquid chromatography quadrupole time-of-flight MS for identification of electron beam from accelerator degradation products of aflatoxin B_1. *Applied Biochemistry and Biotechnology, 175*(3), 1548–1556.

Wang, S.-Q., Huang, G.-Q., Li, Y.-P., Xiao, J.-X., Zhang, Y., & Jiang, W.-L. (2015). Degradation of aflatoxin B_1 by low-temperature radio frequency plasma and degradation product elucidation. *European Food Research and Technology, 241*(1), 103–113.

Wang, X., Qin, X., Hao, Z., Luo, H., Yao, B., & Su, X. (2019). Degradation of four major mycotoxins by eight manganese peroxidases in presence of a dicarboxylic acid. *Toxins, 11*(10), 566.

Wang, Y., King, J. M., Xu, Z., Losso, J., & Prudente, A. (2008). Lutein from ozone-treated corn retains antimutagenic properties. *Journal of Agricultural and Food Chemistry, 56*(17), 7942–7949.

Wang, Y., Zhang, H., Yan, H., Yin, C., Liu, Y., Xu, Q., … Zhang, Z. (2018). Effective biodegradation of aflatoxin B_1 using the *Bacillus licheniformis* (BL010) strain. *Toxins, 10*(12), 497.

Wang, Y., Zhao, C., Zhang, D., Zhao, M., Zheng, D., Lyu, Y., … Cui, Z. (2017). Effective degradation of aflatoxin B_1 using a novel thermophilic microbial consortium TADC7. *Bioresource Technology, 224*, 166–173.

Wei, H., & Wang, E. (2013). Nanomaterials with enzyme-like characteristics (nanozymes): Next-generation artificial enzymes. *Chemical Society Reviews, 42*(14), 6060–6093.

WHO. (1999). High-dose irradiation: wholesomeness of food irradiated with doses above 10 kGy. Report of a joint FAO/IAEA/WHO study group. World Health Organization technical report series, 890 (i-vi), 1-197.

Wu, Y. Z., Lu, F. P., Jiang, H. L., Tan, C. P., Yao, D. S., Xie, C. F., & Liu, D. L. (2015). The furofuran-ring selectivity, hydrogen peroxide-production and low Km value are the three elements for highly effective detoxification of aflatoxin oxidase. *Food and Chemical Toxicology, 76*, 125–131.

Xia, X., Zhang, Y., Li, M., Garba, B., Zhang, Q., Wang, Y., … Li, P. (2017). Isolation and characterization of a *Bacillus subtilis* strain with aflatoxin B_1 biodegradation capability. *Food Control, 75*, 92–98.

Xie, Y., Wang, W., & Zhang, S. (2019). Purification and identification of an aflatoxin B_1 degradation enzyme from *Pantoea* sp. T6. *Toxicon, 157*, 35–42.

Xiong, K., Liu, H., & Li, L. (2012). Product identification and safety evaluation of aflatoxin B_1 decontaminated by electrolyzed oxidizing water. *Journal of Agricultural and Food Chemistry, 60*(38), 9770–9778.

Xu, C., Ye, S., Cui, X., Song, X., & Xie, X. (2019). Modelling photocatalytic detoxification of aflatoxin B_1 in peanut oil on TiO_2 layer in a closed-loop reactor. *Biosystems Engineering, 180*, 87–95.

Xu, L., Eisa Ahmed, M. F., Sangare, L., Zhao, Y., Selvaraj, J. N., Xing, F., … Liu, Y. (2017). Novel aflatoxin-degrading enzyme from *Bacillus shackletonii* L7. *Toxins, 9*(1), 36.

Xu, T., Xie, C., Yao, D., Zhou, C. Z., & Liu, J. (2017). Crystal structures of aflatoxin-oxidase from *Armillariella tabescens* reveal a dual activity enzyme. *Biochemical and Biophysical Research Communications, 494*(3–4), 621–625.

Yu, X., Han, J., Li, H., Zhang, Y., & Feng, J. (2018). The effect of enzymes on release of trace elements in feedstuffs based on in vitro digestion model for monogastric livestock. *Journal of Animal Science and Biotechnology, 9*(1), 73.

Zeinvand-Lorestani, H., Sabzevari, O., Setayesh, N., Amini, M., Nili-Ahmadabadi, A., & Faramarzi, M. A. (2015). Comparative study of in vitro prooxidative properties and genotoxicity induced by aflatoxin B_1 and its laccase-mediated detoxification products. *Chemosphere, 135*, 1–6.

Zhang, L., Ma, Q., Ma, S., Zhang, J., Jia, R., Ji, C., & Zhao, L. (2016). Ameliorating effects of *Bacillus subtilis* ANSB060 on growth performance, antioxidant functions, and aflatoxin residues in ducks fed diets contaminated with aflatoxins. *Toxins, 9*(1), 1.

Zhang, Q., Xiong, K., Tatsumi, E., Li, L.-T., & Liu, H.-J. (2012). Elimination of aflatoxin B_1 in peanuts by acidic electrolyzed oxidizing water. *Food Control, 27*(1), 16–20.

Zhang, W., Xue, B., Li, M., Mu, Y., Chen, Z., Li, J., & Shan, A. (2014). Screening a strain of *Aspergillus niger* and optimization of fermentation conditions for degradation of aflatoxin B_1. *Toxins, 6*(11), 3157–3172.

Zhang, Y., Geary, T., & Simpson, B. K. (2019). Genetically modified food enzymes: A review. *Current Opinion in Food Science, 25*, 14–18.

Zhao, L. H., Guan, S., Gao, X., Ma, Q. G., Lei, Y. P., Bai, X. M., & Ji, C. (2011). Preparation, purification and characteristics of an aflatoxin degradation enzyme from *Myxococcus fulvus* ANSM068. *Journal of Applied Microbiology, 110*(1), 147–155.