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REVIEW PAPER

Biological degradation of aflatoxin by microbe and enzyme: a review

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Abstract: Aflatoxins, produced by fungi like Aspergillus flavus and Aspergillus parasiticus, pose significant threats to food safety, impacting human and animal health while causing economic losses. Detoxifying aflatoxins is crucial to reducing contamination in food and feed. Enzymes and microorganisms present an eco-friendly and efficient solution for this purpose. This review highlights their roles in detoxification, focusing on bacteria, yeasts, and fungi that can degrade or bind aflatoxins, thereby lowering toxicity. Enzymes such as laccase, peroxidase, and reductase facilitate detoxification through oxidative and hydrolytic degradation. The efficiency of these methods depends on factors like pH, substrate availability, and temperature. Understanding the interactions between enzymes, microorganisms, and aflatoxins is essential for optimizing detoxification strategies. While promising, further research is needed to enhance their application in food safety.

Keywords: microbe, enzyme, aflatoxin, biodegradation

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INTRODUCTION

Food contamination by mycotoxins is a serious global issue that affects human and animal health and causes significant economic losses both locally and internationally [1]. The growth of fungi, which are the primary producers of mycotoxins, is greatly influenced by climate and geography. Tropical countries with high rainfall, humidity, and warm temperatures promote the development of mycotoxin-producing fungi such as *Aspergillus spp*., *Fusarium spp*., Penicillium, and Alternaria [2]. These fungi often contaminate agricultural and livestock products such as legumes, cereals, corn, meat, eggs, milk, and other products like copra, pepper, spices, coffee, herbal products, and fish [3].

Mycotoxins are secondary metabolites produced by toxicogenic fungi in food and feed, causing toxic effects on humans and animals when ingested [4]. Exposure to mycotoxins through food can lead to diseases known as mycotoxicosis [5]. Mycotoxins are carcinogenic, and their toxicity can cause mutagenicity, genotoxicity, immunotoxicity, and neurotoxicity. Among various types of mycotoxins, five main types of concern are aflatoxins, ochratoxins, fumonisins, trichothecenes, and zearalenone. According to the FAO, approximately 25% of the world's food is contaminated with mycotoxins [6], with 25%-50% of agricultural commodities contaminated with these five types of mycotoxins [7].

Aflatoxin is the most toxic and carcinogenic mycotoxin, posing a major global food safety issue. Data shows that a significant portion of feed samples from various countries are contaminated with aflatoxin B1 (AFB1) exceeding EU limits [8]. Additionally, 73.6% of UHT milk samples contain aflatoxin M1 (AFM1) above the legal limits set by the EU [9]. This

mycotoxin poses a threat to health, especially for infants and children [10].

Aflatoxins are challenging to remove from food materials due to their high stability. Detoxification methods include physical, chemical, and biological approaches; however, physical and chemical methods are often impractical due to their high costs and potential negative impacts on food quality [11]. Biological methods, such as fermentation with microorganisms, offer a more environmentally friendly and cost-effective solution, as they can reduce aflatoxins without compromising the nutritional value of food [12]. Fermentation with lactic acid bacteria, such as *Lactobacillus* and *Bifidobacterium*, has proven effective in detoxifying aflatoxins while also promoting digestive health [13].

Advancements in science and technology have identified various microorganisms and enzymes effective in reducing aflatoxins. Genetic engineering technology enables the development of strains with higher detoxification activity [14]. However, industrial challenges such as the stability of microorganisms, production costs, and regulatory acceptance still need to be addressed. Another innovative approach involves the use of aflatoxin-degrading enzymes, which are capable of breaking down the chemical structure of aflatoxins, thus reducing their toxicity [15]. Different types of microorganisms, including bacteria and fungi, have been identified as producers of these enzymes, offering potential solutions for aflatoxin detoxification. Ongoing research into the production and mechanisms of aflatoxin-degrading enzymes is crucial for advancing their practical applications in the food and feed industries, providing more effective methods for mitigating aflatoxin contamination and its associated risks.

This article reviews the role of microorganisms and enzymes in aflatoxin detoxification, highlighting recent research and future prospects. The main focus is on the mechanisms of action of microorganisms and enzymes as detoxifying agents, as well as the challenges that need to be overcome to enhance food safety. It is hoped that innovative and efficient strategies can be developed to reduce the global risk of aflatoxin contamination.

RESEARCH METHODS

The research method in this study involves a literature review focused on microorganisms and enzymes that act as aflatoxin detoxifying agents. The sources were selected from several databases, including Google Scholar, PubMed, and Scopus, with articles published between 2005 and 2024. The keywords employed include “microbe and enzymes mechanisms Aflatoxin biodetoxification LAB recent study future prospect fermented food.” A systematic approach was used to filter thousands of publications from 16,600 down to 112 relevant studies. Inclusion and exclusion criteria were established based on publication year and topic relevance, using specific keywords and selecting highly cited studies. Abstracts and conclusions were examined to assess suitability and focus on recent studies. Data processing involved compiling research results related to the topic. Various aspects regarding the role of microorganisms and enzymes in aflatoxin detoxification will be explained simply using descriptive analysis.

RESULTS AND DISCUSSION

Aflatoxin-Producing Fungi

The aflatoxin-producing fungus *Aspergillus* subgenus *Circumdati* section *Flavi*, also known as the *Aspergillus flavus* group, has attracted global attention due to its industrial relevance and toxicogenic potential. This section is classified into two categories: aflatoxin-producing species and non-aflatoxin-producing species [16]. The aflatoxin-producing species in this group are widely recognized as common contaminants in food and animal feed.Aflatoxin-producing species, such as *Aspergillus flavus* and *Aspergillus parasiticus*, are capable of biosynthesizing aflatoxins and are commonly found contaminating food and feed [17]. These species produce four primary aflatoxins—B1, B2, G1, and G2—all of which are highly hazardous due to their carcinogenic properties [18]. Aflatoxin biosynthesis is strongly influenced by various factors, including the substrate, humidity, temperature, pH, aeration, and the presence of competing microflora [19].

The growth of *Aspergillus flavus* and *A. parasiticus* occurs at temperatures between 20 and 30 °C with a relative humidity (RH) range of 60-80% [20]. The genes responsible for aflatoxin biosynthesis are *aflS* and *aflJ*. These genes are activated at 28 °C, peak at 30 °C, and their expression significantly decreases at temperatures exceeding 37 °C [21]. These fungi are typically found in soil and decaying organic matter, and they can contaminate various agricultural products, including corn, peanuts,

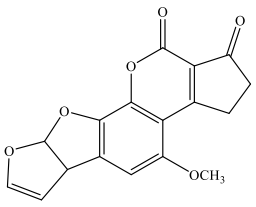
cotton seeds, rice, and milk. High humidity facilitates the growth of *A. flavus* and aflatoxin production, while anaerobic conditions hinder their growth, reducing the likelihood of aflatoxin contamination [22].

Non-aflatoxin-producing species like *Aspergillus oryzae*, *A. sojae*, and *A. tamarii* are commonly used in the production of fermented foods such as soy sauce in Indonesia and sake in Japan. Through genetic mutations, *A. oryzae* and *A. sojae* have lost their ability to produce aflatoxins, making them safe for use in the fermentation industry [23]. Genetic studies also reveal that *A. oryzae* exhibits considerable aflatoxin B1 (AFB1) degrading activity, highlighting its potential for AFB1 detoxification in food systems [10].

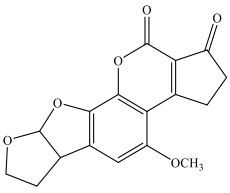
Physicochemical Properties of Aflatoxins

Aflatoxins were first isolated from *Aspergillus flavus* in the UK in 1960, and contamination by this mycotoxin led to the outbreak of "Turkey X Disease," which resulted in the death of over 100,000 turkeys [24]. Aflatoxins, short for *Aspergillus flavus* toxins, are toxic secondary metabolites produced by *Aspergillus* spp. that can contaminate various food products [25].

Aflatoxins belong to the class of difuranocoumarin compounds, with twenty structural variations of cyclic polyketides [26]. However, the most commonly encountered aflatoxins are aflatoxin B1 (AFB1), aflatoxin B2 (AFB2), aflatoxin G1 (AFG1), aflatoxin G2 (AFG2), aflatoxin M1 (AFM1), and aflatoxin M2 (AFM2) [24]. The melting points of aflatoxins B1, B2, G1, and G2 are reported to be 268°C-269°C, 268°C-289°C, 244°C-246°C, and 240°C-247°C, respectively [27].



Aflatoxin B_1



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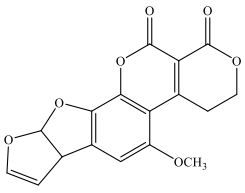
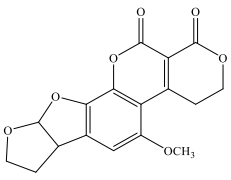
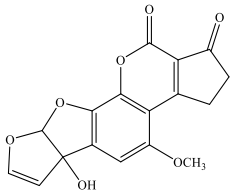


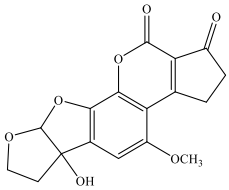
Aflatoxin G_1



Aflatoxin G_2



Aflatoxin M_1



Aflatoxin M_2

Figure 1.Chemical Structure of Aflatoxin B1, B2, G1, G2, M1 & M2

Figure 1 illustrates that all aflatoxins are heterocyclic compounds sharing a common benzene ring, with differences in double bonds and ketone groups. Their metabolites have hydroxyl groups at various positions, making aflatoxins slightly soluble in water and prone to epoxidation, which affects their excretion and toxicity [28]. Physically, aflatoxins are colorless to pale yellow crystalline solids with low water solubility but dissolve well in polar organic solvents like methanol, ethanol, acetone, chloroform, and acetonitrile. They are less soluble in ethyl acetate, diethyl ether, and benzene, and poorly soluble in petroleum ether and n-hexane, leading to precipitation; this aids extraction by separating aflatoxins from fats and pigments [29].

Aflatoxins exhibit high thermal stability, remaining intact above 100°C, so processes like milk pasteurization fail to eliminate them. Besides thermal stability, AFB1 is sensitive to UV light and extreme pH (below 3 or above 10), and its lactone group reacts with ammonia or hypochlorite, properties leveraged in food and feed decontamination methods [30]. Among about twenty aflatoxin types, B1, B2, G1, and G2 are most significant. Named by their light absorption and fluorescence, B1 and B2 fluoresce blue under UV at 425 nm, while G1 and G2 fluoresce green at 540 nm [31]. AFM1, AFB1's main metabolite formed via cytochrome P450 1A2 hydroxylation, emits strong blue-purple fluorescence [32].

Aflatoxins commonly contaminate tropical and subtropical food products such as grains, nuts, corn, rice, coconut/copra, and dairy [2]. Contamination depends heavily on temperature and water activity (aw), crucial for fungal growth and aflatoxin biosynthesis [33]. Optimal aflatoxin production occurs above 20% moisture, aw near 0.99, and temperatures of 29–30°C (Tejero et al., 2021). Aspergillus flavus and A. parasiticus thrive at aw 0.90–0.98 at 27°C or 0.90–0.94 aw at 35°C, with AFB1 production optimal at 27°C [34].

Occurrence of aflatoxin

In the United States, aflatoxin contamination is most commonly associated with peanut and corn crops [35]. While strict monitoring by the FDA has helped mitigate risks, contamination incidents still occur, particularly in imported products from countries with less stringent regulations. Risk assessments using the Margin of Exposure (MOE) approach and quantitative liver cancer risk models developed by EFSA and FAO/WHO suggest that AFB1 exposure through the consumption of corn and peanuts in Indonesia warrants concern [36]. The MOE values are typically below 10,000, with some reports showing values under 1,000. Estimates indicate that liver cancer cases linked to AFB1 exposure could exceed 0.1 per 100,000 individuals over 75 years old [37]. This highlights the need for effective management of AFB1 risk in Indonesia. Aflatoxin contamination in food and feed across multiple countries is summarized in Table 1.

Table 1. Aflatoxin Contamination in Food and Feed in Various Countries

No.	Food	Country	Average Levels of Contaminated Samples (µg/kg)	Incidence % (Contaminated Samples)	Ref.
1.	Maize and groundnut	Ghana	0.60 to 1065 and 0.20 to 627	98% and 70%	[38]
2.	Milk and Dairy Products	Malaysia	0.0035 - 0.1005	35.8 (53)	[39]
3.	Wheat and Wheat Biscuits	China	0.03 - 0.12	5.6 (178)	[40]
4.	Soy Pasta	Korea	0.88 - 16.17	24.4 (45)	[41]
5.	Cashews	Brazil	0 - 122.35	42 (12)	[42]
6.	Cereal-based baby foods	Turkey	0.03±0.01	11 (12.9)	[43]
7.	Tea	Pakistan	0.11 - 16.17	78.3 (94)	[44]
8.	Red Chili and Black Pepper	India	0 - 219.6	85.4 (55)	[45]
9.	Fish Feed (Factory)	Uganda	<40	48	[46]
10.	Boiled Peanuts	Indonesia	<0.92	120 (31.3)	[47]

The presence of aflatoxin in animal feed presents significant risks, leading to the contamination of meat, milk, and eggs with residues such as aflatoxin M1 (AFM1) [48]. Aflatoxin is a major threat to both food safety and human health, making the rapid and accurate detection of aflatoxin in food samples essential. Various detection technologies are employed for this purpose, including traditional methods like TLC (thin-layer chromatography), HPLC (high-performance liquid chromatography) [49], ELISA (enzyme-linked immunosorbent assay), GICA (colloidal gold immunochromatography) [50], RIA (radioimmunoassay) [51], FS (fluorescence spectroscopy) [52], LC-MS/MS [53], and molecular techniques like PCR for detecting aflatoxin-related genes [54]. The choice of the analytical method depends on factors such as the sample matrix type, available equipment, toxin concentration, detection limits, accuracy, sensitivity, selectivity, analysis time, and the level of personnel expertise required [26].

Aflatoxin Toxicity and Health Impacts

Aflatoxin is a fat-soluble toxin that easily enters the bloodstream and poses serious health risks to humans and animals through contaminated food, dairy products, or inhalation of aflatoxin dust, particularly AFB1, in industrial environments [55]. Skin exposure to AFB1 under certain conditions also presents health

hazards [56]. Acute aflatoxicosis can result from high-dose short-term ingestion, potentially causing death. Chronic low-to-moderate exposure weakens the immune system, stunts growth in children, and significantly increases liver cancer risk. Globally, there are about 782,200 new liver cancer cases annually, with 83% occurring in developing countries. Approximately 28.2% of these cancers are linked to aflatoxin, with 40% of cases in Africa [57].

In the liver, aflatoxin B1 (AFB1) undergoes biotransformation by cytochrome P450 enzymes and aryl hydrocarbon hydroxylase, forming reactive intermediates such as lipid peroxides and AFB1-8,9-epoxide, which cause cellular damage. The conversion to exo-8,9-epoxide is a critical step in AFB1's genotoxic and carcinogenic effects [58]. Toxic effects vary by species, sex, age, and exposure level, with AFB1 being the most toxic among aflatoxins [59,60]. The FAO sets limits for AFB1 at 5–50 µg/kg in animal feed and 1–20 µg/kg in food. Symptoms of acute exposure include nausea, jaundice, vomiting blood, seizures, and possibly death [61]. The International Agency for Research on Cancer (IARC) classifies AFB1 as a potent liver carcinogen with an LD50 of 12–16 mg/kg body weight [62]. Hepatocellular carcinoma is closely linked to aflatoxin exposure [63]. WHO categorizes aflatoxins B1, B2, G1, and G2 as Group 1 carcinogens, while AFM1 is Group 2B [64].

Aflatoxin Detoxification Methods

To mitigate health risks to humans and animals and reduce economic losses caused by aflatoxin contamination in food and feed, several degradation and detoxification methods have been developed. These methods fall into three main categories: physical, chemical, and biological, each with unique mechanisms and applications (Table 2). Chemical treatments are often highly effective; for example, lactic acid applied to pistachios can reduce aflatoxin levels by up to 99.90% [51]. Similarly, citric acid treatment on walnuts achieves 99.00% degradation through oxidation [51]. Propionic acid reduces aflatoxin content in peanuts by 96.07% due to its antimicrobial activity [51]. Ozonation in wheat reduces aflatoxins by 85-95% [65], while active redox enzymes in liquid coffee degrade aflatoxins by up to 96% [66]. Sodium hydrosulfite treatment on black pepper also achieves 96% degradation via reduction reactions [67].

Physical methods include UV light, gamma irradiation, cooking, washing, and filtration. UV light reduces aflatoxin levels in milk by 65-100%, depending on exposure and intensity [68]. Gamma irradiation effectively degrades aflatoxins in grains like corn, wheat, and rice, with rates between 15.54-69.29% [69]. Cooking corn at 90°C reduces aflatoxins by 51-85% [70], while washing corn removes up to 95% of toxins [71]. Carbon filtration in liquid coffee achieves 74-79% reduction [72]. Biological approaches use microorganisms and enzymes to detoxify aflatoxins safely and sustainably. Probiotics such as *Lactobacillus bulgaricus* and *Bifidobacterium lactis* in UHT milk reduce aflatoxins by 38% [73]. A combination of *Saccharomyces cerevisiae* and *Lactobacillus plantarum* can completely eliminate aflatoxins in milk [74]. Additionally, *Streptococcus thermophilus* and *Saccharomyces cerevisiae* reduce aflatoxins in baby food by 94% [75], and *Pichia occidentalis* in kombucha degrades 97% of aflatoxins [76]. Overall, while chemical methods generally achieve near-complete degradation, biological and physical methods show promising potential for application in food safety depending on the product and conditions used.

Table 2. Aflatoxin Degradation Methods

Method	Treatment	Product	% Degradation	Ref.
Chemical	Lactic Acid	Pistachio	99.90%	[51]
	Citric Acid	Walnuts	99.00%	[51]
	Propionic Acid	Peanuts	96.07%	[51]
	Ozone Treatment	Wheat	85-95%	[65]
	Active Redox Enzymes	Aflatoxin-spiked Liquid Coffee	<96%	[66]
	Sodium Hydrosulfite	Black Pepper	96%	[67]
Physical	UV Light	Milk	65-100%	[68]

Method	Treatment	Product	% Degradation	Ref.
	Gamma Irradiation	Corn	15.54-60.26%	[69]
	Gamma Irradiation	Wheat	22.25-69.29%	[69]
	Gamma Irradiation	Rice	27.46-64.68%	[69]
	Cooking at 90°C	Corn	51-85%	[70]
	Washing	Corn	95%	[71]
	Carbon Filtration	Aflatoxin-spiked Liquid Coffee	74-79%	[72]
Biological	*Hanseniaspora opuntia, Candida sorboxylosa*, *Pichia occidentalis*	Kombucha	97%	[73]
	Saccharomyces cerevisiae, *Streptococcus thermophilus*, *Kluyveromyces lactis Bifidobacterium bifidum*	Baby Food	94%	[74]
	L. helveticus ATCC 12046, *L. lactis* JF 3102, *L. plantarum* NRRLB-4496, *Saccharomyces cerevisiae*,	Milk	100%	[75]
	Bifidobacterium lactis, L. rhamnosus, *Lactobacillus bulgaricus*	UHT Milk	38%	[76]

Comparative Assessment of Detoxification Methods

Each detoxification method has its own advantages and limitations. Chemical methods are generally the most effective in terms of degradation percentage, often achieving more than 90% reduction. However, they can produce toxic residues or alter the quality of food, and require careful handling and regulation. Physical methods, although safer and easier to apply, usually result in only partial degradation and may not completely eliminate mycotoxins. Some physical treatments can also affect the sensory and nutritional properties of food [30].

In contrast, biological methods—especially those involving microorganisms and enzymes—offer a safer and more environmentally friendly approach. These methods do not leave harmful residues, act specifically, and can be applied during food processing and storage. Biological methods are also more sustainable, cost-effective in the long run, and suitable for fermented products. However, their effectiveness can vary depending on strain selection, substrate type, and environmental conditions [78].

Overall, although chemical methods may offer high degradation rates, biological approaches are more favorable in terms of food safety, environmental impact, and consumer acceptability. Therefore, integrating biological strategies with optimized physical or mild chemical methods could offer a comprehensive solution for aflatoxin detoxification in the food industry.

A major challenge is that aflatoxin contamination cannot be entirely avoided. Thus, appropriate handling strategies are essential for contaminated food products. These strategies must meet several criteria: they should not produce toxic compounds or harmful residues, must preserve the nutritional and sensory quality of the product, and be economically and technically feasible while effectively inactivating spores and mycelia of aflatoxin-producing fungi [77].

Mechanism of Aflatoxin Biodetoxification by Microorganisms and Enzymes

Biodetoxification refers to the process of converting toxic compounds into non-toxic forms using biological agents such as microorganisms and enzymes. This process involves specific biochemical mechanisms that depend on the type and strain of microorganism or enzyme used [78].

Microorganisms detoxify aflatoxins through multiple strategies, including inhibition of toxin-producing fungal growth via competition for nutrients and space, adsorption of aflatoxins onto their cell walls, and degradation through enzymatic and metabolic activity. For example, *Lactobacillus kefiri* and *Saccharomyces cerevisiae* are known to effectively detoxify aflatoxins [79]. Co-cultivation studies have shown that when *Aspergillus parasiticus* and *A. flavus* are cultured in the presence of

Salmonella, spore production and the levels of aflatoxins AFB1 and AFB2 are reduced [78].

Many microorganisms have demonstrated the ability to degrade or adsorb aflatoxins. Members of the *Bacillaceae* family, such as *B. pumilus*, *B. velezensis*, *B. licheniformis*, and *B. subtilis*, are capable of degrading aflatoxins [80]. Lactic acid bacteria (LAB) like *L. kefiri*, *L. plantarum*, *L. delbrueckii*, and *L. rhamnosus* exhibit both adsorption and degradation abilities, along with *Enterococcus faecium*, *E. coli*, and *Tetragenococcus halophilus* [81]. Additionally, fungi such as *S. cerevisiae*, *A. niger*, *Trametes versicolor*, and yeasts like *Pichia occidentalis* and *Candida versatilis* contribute to mycotoxin detoxification [82,83].

LAB are frequently studied due to their ability to inhibit fungal growth through lactic acid fermentation, which lowers environmental pH and blocks aflatoxin synthesis. LAB also possess probiotic properties, can bind toxins, and are considered safe for use, making them suitable for food and feed applications [84]. The adsorption of aflatoxins onto microbial cell walls occurs through non-covalent interactions (e.g., Van der Waals forces), where the cell wall acts as a "sponge." Acidic environments enhance this binding, particularly for *L. plantarum* and *S. cerevisiae* at pH 2.5.

In LAB, aflatoxin adsorption mainly involves components like peptidoglycan, carbohydrates, phosphates, and proteins. Binding mechanisms include ion exchange, physical interactions, and complexation. The composition and structure of cell walls affect the binding ability, with variations in peptidoglycan structure and binding site availability playing significant roles [78].

The efficiency of aflatoxin binding by *L. plantarum* is influenced by incubation time, temperature, pH, and the bacterial state (live or dead). Heat and acid treatments can increase the hydrophobicity of the cell surface and expose additional binding sites. Optimal binding occurs at pH 2.5, while pH 8.5 shows minimal adsorption [84].

Table 3. Microorganisms from Fermented Foods that Effectively Detoxify Aflatoxin

Fermented Food	Microorganism	Aflatoxin Reduction (%)	Reduction Mechanism	Ref.
Kefir Culture	*Kazachstania servazzii*, *Acetobacter syzygii, Lactobacillus kefiri*,	82–100	Adsorption	[85]
Kombucha Drink	*Hanseniaspora opuntiae, Candida sorboxylosa*, *Pichia occidentalis*	9,7	Enzymatic degradation and Adsorption	[86]
Fermented Iru from Peas	*Bacillus subtilis* BCC 42005	-	Enzymatic degradation via extracellular fractions	[87]
Chinese Soy Fermentation	*Aspergillus niger*	98.65	Glutathione-mediated biotransformation	[88]
Fermented Soy Sauce	*Tetragenococcus halophilus*	91.99	Adsorption with enzymatic degradation	[89]
Fermented Corn (Kenkey) and Sorghum Beer (Pito)	*Saccharomyces cerevisiae*	40	Contains bacteriocin with antifungal activity	[90]

Some bacteria can suppress aflatoxin production by downregulating fungal genes involved in toxin biosynthesis. Metabolites released during bacterial growth can alter environmental conditions such as temperature, humidity, pH, and substrate properties, disrupting fungal growth [91]. However, growth inhibition alone is insufficient for complete aflatoxin detoxification, necessitating further studies on more effective approaches.

LAB and other microbes produce secondary metabolites with antifungal activity. These include organic acids (lactic, formic, butyric, propionic, hexanoic, caproic, benzoic, phenyl lactate), antifungal peptides, diacetyl, phenolic compounds, reuterin, and bacteriocins [84].

Various enzymes also contribute to aflatoxin detoxification. Aflatoxin oxidase (AFO), produced by *Armillariella tabescens*, oxidizes aflatoxins into less toxic forms [92]. Laccase, from white-rot fungi, degrades aromatic bonds in aflatoxins [93]. Peroxidases from *Pseudomonas* species use hydrogen peroxide for aflatoxin oxidation [94], while reductases from *Mycobacterium smegmatis* reduce the toxin's structure [95]. Manganese peroxidase from *Pleurotus ostreatus* facilitates the breakdown of aflatoxins using Mn^{2+} ions [96]. Certain *Bacillus* species, such as *B. mycoides*, *B. cereus*, *B. anthracis*, and *B. subtilis*, produce AHL lactonases that detoxify aflatoxin B1 (AFB1) by cleaving the lactone ring [97].

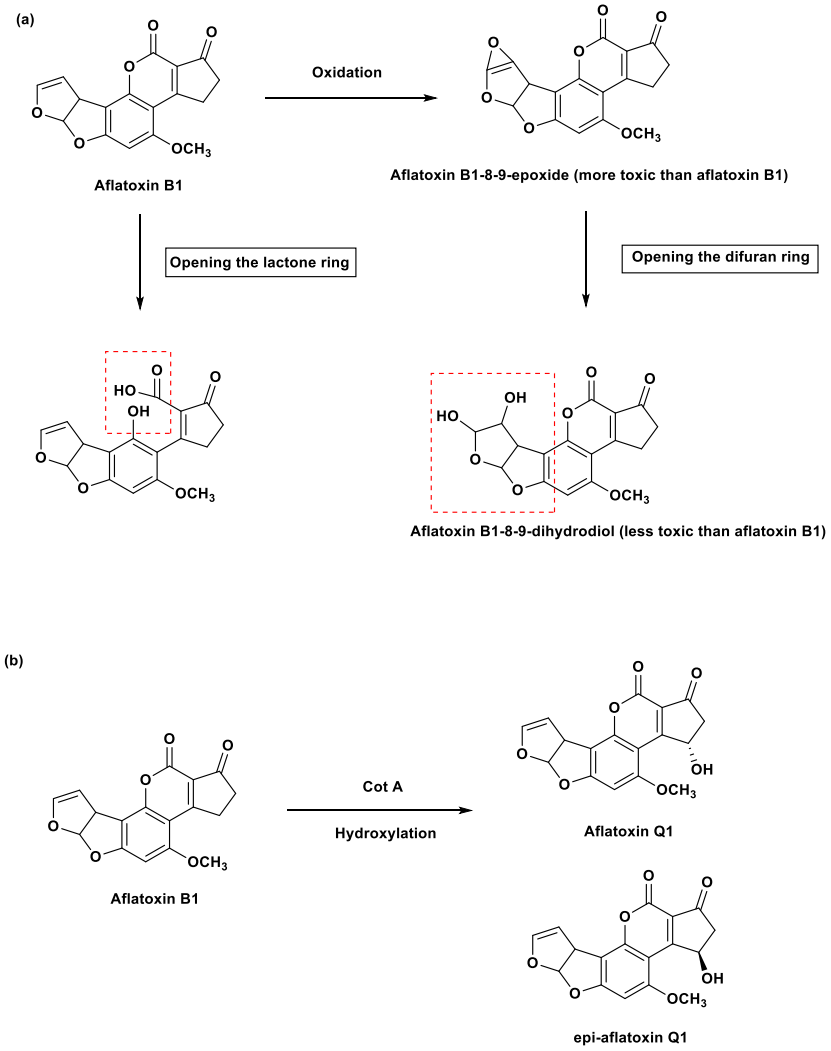


Figure 2. *Laccase-mediated degradation pathway of aflatoxin B1:*(a) Laccase targets the lactone and furan rings, reducing aflatoxin B1 toxicity [99]; (b) Hydroxylation at carbon 3 (C3) forms two isomers: aflatoxin Q1 and epi-aflatoxin Q1 [100].

LAB can also enzymatically degrade aflatoxins in fermented foods through bioadsorption and enzymatic hydrolysis. They produce protein hydrolases such as cell wall proteases, peptide transporters, and intracellular peptidases, which reduce aflatoxin toxicity [84].

Aflatoxins contain a difuran ring and a coumarin lactone ring, both of which are associated with mutagenic and carcinogenic properties. Enzymes target these sites during detoxification. Laccase, one of the most studied enzymes, degrades AFB1 through two main mechanisms: modifying the furan ring to form AFB1-epoxide and subsequently AFB1-dihydrodiol, and opening the lactone ring by hydroxylating carbon positions 10 and 11 [93]. Wang et al. (2011) reported the conversion of AFB1 to its epoxide and dihydrodiol forms through laccase activity [100], while Guo et al. (2020) observed that CotA laccase from *B. licheniformis* produces AFQ1 and epi-AFQ1 [99]. Borgomano (2015) explained that laccase

also facilitates dehydrogenation, hydroxylation, dehydration, and removal of various functional groups [101].

In summary, biological detoxification of aflatoxins using microbes and enzymes is a promising approach for food and feed safety. Future research should prioritize microbial screening, optimization of detoxifying enzyme production, and biotechnological innovations to enhance application in agriculture, food processing, and environmental management.

Economic Impact of Aflatoxins

The economic losses due to mycotoxin contamination, particularly aflatoxins, are significant. Between 2006 and 2016, the prevalence of aflatoxins in cereals across Africa, America, Asia, and Europe reached 55%, with annual losses in the U.S. amounting to USD 500 million. In China, aflatoxin contamination has led to the loss of 21 million tons of harvest, representing approximately 4.2% of the country's annual yield [102]. In Africa, economic losses due to aflatoxin contamination exceed USD 750 million annually [103]. Developing countries are particularly impacted in export markets, facing shipment rejections and lower selling prices. The economic burden also extends to the livestock sector, where aflatoxins reduce productivity, weight gain, feed efficiency, fertility, and disease resistance, ultimately affecting the quality and quantity of meat, milk, and eggs [104]. In Indonesia, the Philippines, and Thailand, approximately 5% of corn and peanut production is discarded due to aflatoxin contamination [105]. Furthermore, Khachatryan et al. (2005) estimated that the adoption of European Union aflatoxin standards could reduce trade flows from developing countries by 1.07% [105].

Prevention and Regulation of Aflatoxins

Aflatoxin B1, recognized as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC), presents a significant threat to global food security [106]. Although it is impossible to completely eliminate aflatoxin contamination in food products, its prevention and reduction can be achieved through effective management practices both pre- and post-harvest. These include Hazard Analysis and Critical Control Point (HACCP), Good Agricultural Practices (GAP), Good Handling Practices (GHP), Good Manufacturing Practices (GMP), and Good Distribution Practices (GDP) [77]. The factors are crucial for maintaining the safety, quality, and nutritional integrity of food delivered to consumers.

Critical points in post-harvest handling that are vulnerable to *Aspergillus flavus* infection include harvesting, drying, and storage. Effective control measures focus on managing moisture levels, applying high temperatures to eliminate fungi, and using phosphine fumigation to inhibit fungal mycelium growth [77]. To mitigate aflatoxin contamination, policies should prioritize: (1) raising awareness among stakeholders across the value chain (farmers, consumers, processors, and traders) about contamination sources and their health risks; (2) adopting robust strategies to manage Aspergillus infections both pre- and post-harvest; and (3) promoting the development and accessibility of affordable technologies and infrastructure for monitoring contamination levels [107].

An estimated 4.5 billion people globally are at risk of exposure to aflatoxin contamination [108]. Due to the harmful impacts of aflatoxins on living organisms, regulatory agencies have established maximum allowable levels for aflatoxins in food and feed intended for human and animal consumption. The European Commission and the U.S. Food and Drug Administration (FDA) have set this limit at 20 parts per billion (ppb), while the European Union enforces a more stringent standard of 4 ppb [109].

International regulations on aflatoxins involve several global organizations, such as the World Health Organization (WHO), the Food and Agriculture Organization (FAO), and the Codex Alimentarius Commission. These bodies play key roles in shaping World Trade Organization (WTO) agreements and overseeing global food safety standards [110]. At the regional level, the European Union enforces strict aflatoxin limits to safeguard consumer health, which all member states must adhere to [111]. In the United States, the Food and Drug Administration (FDA) sets maximum allowable levels for aflatoxins in food and animal feed and conducts regular monitoring to ensure compliance [112]. However, stringent regulations in developed countries can pose challenges for producers in developing nations, who often lack adequate scientific and technological resources. Effective aflatoxin prevention requires a collaborative, multi-sectoral approach involving governments, the food industry, and farmers, supported by resource availability and adherence to regulations.

Recent Advances in Aflatoxin Detoxification Technology

Recent biotechnological approaches have developed more effective and specific methods for aflatoxin detoxification. Genetic engineering using CRISPR-Cas has produced modified microbes with enhanced aflatoxin degradation activity, resistant to food processing conditions, and capable of breaking down aflatoxins more efficiently (Fang et al., 2025 and Zhao et al., 2023). Synthetic biology supports the development of engineered enzyme consortia that work synergistically, improving the stability and efficacy of aflatoxin degradation (Wang et al., 2023).

Nanotechnology also plays a significant role through nano-biosensors for rapid detection and nano-delivery systems that enhance the stability and bioavailability of detoxifying enzymes and microbes (Singh et al., 2023). Industrial-scale studies demonstrate practical applications, such as corn feed fermentation using *Lactobacillus plantarum* which reduces aflatoxin contamination by up to 85% without compromising nutritional value (Liu, 2022).

These advances integrate microbial biotechnology, enzyme engineering, and nanotechnology to provide safe, effective, and sustainable aflatoxin detoxification solutions, supporting food safety and public health in aflatoxin-prone regions.

CONCLUSION

Aflatoxin detoxification using microorganisms and enzymes involves various mechanisms that transform aflatoxins into less toxic compounds. Microorganisms work by inhibiting the growth of aflatoxin-producing fungi, adsorbing toxins through cell wall binding, or producing antifungal compounds that alter the environmental pH and suppress toxin biosynthesis. Meanwhile, enzymes such as laccase, peroxidase, and reductase can degrade aflatoxins through oxidation, hydrolysis, or reduction reactions, converting them into non-toxic or significantly less harmful metabolites. These processes occur under mild conditions, with high specificity and minimal impact on food quality.

Integrating preventive measures—such as proper drying and storage—with these biotechnological strategies has proven effective in reducing contamination risks. This approach is especially relevant in tropical and subtropical regions where aflatoxin exposure is prevalent. Microbial and enzymatic detoxification offers a sustainable and promising solution to ensure global food and feed safety.

CONFLICT OF INTEREST

The authors confirm that they have no conflicts of interest related to the preparation of this article.

REFERENCES

[1] Abrunhosa, L., Morales, H., Soares, C., Calado, T., Vila-Chã, A. S., Pereira, M., et al. (2016). A review of mycotoxins in food and feed products in Portugal and estimation of probable daily intakes. Critical Reviews in Food Science and Nutrition, 56(2), 249–265. https://doi.org/10.1080/10408398.2012.720619

[2] Alshammari, N. I., Sulieman, A. M. E., & Albulaihed, Y. (2024). Aflatoxins occurrence, toxicity effects and degradation. In Microbial toxins in food systems: Causes, mechanisms, complications, and metabolism (pp. 349–360). Cham: Springer Nature Switzerland.

[3] Nogueira, W. V., Tesser, M. B., & Buffon, J. G. (2024). Assessment of mycotoxins found in farmed fish feed. Aquaculture International, 1–57.

[4] Frisvad, J. C., Møller, L. L., Larsen, T. O., Kumar, R., & Arnau, J. (2018). Safety of the fungal workhorses of industrial biotechnology: Update on the mycotoxin and secondary metabolite potential of Aspergillus niger, Aspergillus oryzae, and Trichoderma reesei. Applied Microbiology and Biotechnology, 102, 9481–9515.

[5] Omotayo, O. P., Omotayo, A. O., Mwanza, M., & Babalola, O. O. (2019). Prevalence of mycotoxins and their consequences on human health. Toxicological Research, 35, 1–7.

[6] Demirel, G. Ö. K. S. U. N., & Doğan, N. N. (2023). Assessment of awareness and behavioral habits to reduce dietary exposure to mycotoxins. Journal of Faculty of Pharmacy of Ankara University, 47(3), 29–29.

[7] Cinar, A., & Onbaşı, E. (2019). Mycotoxins: The hidden danger in foods. Mycotoxins Food Safety, 1–21.

[8] Gruber-Dorninger, C., Jenkins, T., & Schatzmayr, G. (2019). Global mycotoxin occurrence in feed: A ten-year survey. Toxins, 11(7), 375.

[9] Xiong, J., Xiong, L., Zhou, H., Liu, Y., & Wu, L. (2018). Occurrence of aflatoxin B1 in dairy cow feedstuff and aflatoxin M1 in UHT and pasteurized milk in central China. Food Control, 92, 386–390.

[10] Lee, H. J., & Ryu, D. (2017). Worldwide occurrence of mycotoxins in cereals and cereal-derived food products: Public health perspectives of their co-occurrence. Journal of Agricultural and Food Chemistry, 65(33), 7034–7051.

[11] Sipos, P., Peles, F., Brassó, D. L., Béri, B., Pusztahelyi, T., Pócsi, I., & Győri, Z. (2021). Physical and chemical methods for reduction in aflatoxin content of feed and food. Toxins, 13(3). https://doi.org/10.3390/toxins13030204

[12] Marshall, H., Meneely, J. P., Quinn, B., Zhao, Y., Bourke, P., Gilmore, B. F., … Elliott, C. T. (2020). Novel decontamination approaches and their potential application for post-harvest aflatoxin control. Trends in Food Science & Technology, 106, 489–496. https://doi.org/10.1016/j.tifs.2020.11.001

[13] Liu, A., Zheng, Y., Liu, L., Chen, S., He, L., Ao, X., & Liu, S. (2020). Decontamination of aflatoxins by lactic acid bacteria. Current Microbiology, 77(12), 3821–3830. https://doi.org/10.1007/s00284-020-02220-y

[14] Liu, L., Xie, M., & Wei, D. (2022). Biological detoxification of mycotoxins: Current status and future advances. International Journal of Molecular Sciences, 23(3), 1064.

[15] Kumar, V., Bahuguna, A., Ramalingam, S., Dhakal, G., Shim, J. J., & Kim, M. (2022). Recent technological advances in mechanism, toxicity, and food perspectives of enzyme-mediated aflatoxin degradation. Critical Reviews in Food Science and Nutrition, 62(20), 5395–5412.

[16] Katati, B., Kovács, S., Njapau, H., Kachapulula, P. W., Zwaan, B. J., van Diepeningen, A. D., & Schoustra, S. E. (2024). Maize Aspergillus section Flavi isolate diversity may be distinct from that of soil and subsequently the source of aflatoxin contamination. Mycotoxin Research, 1–17.

[17] Rasheed, U., Cotty, P. J., Ain, Q. U., Wang, Y., & Liu, B. (2024). Efficacy of atoxigenic Aspergillus flavus from southern China as biocontrol agents against aflatoxin contamination in corn and peanuts. Pesticide Biochemistry and Physiology, 201, 105887.

[18] Sudini, P., Srilakshmi, K. V. K., & Samuel, M. C. (2015). Detection of aflatoxigenic Aspergillus strains by culture and molecular methods: A critical review. African Journal of Microbiology Research, 9(8), 484–491.

[19] Rai, J. P., Narware, J., Kumar, R. , Kumar, R., Pandey, P., Prakash, N., & Ghatak, A. (2024). Aflatoxin's toll on health: Insights into human and animal impact.

[20] Mannaa, M., & Kim, K. D. (2018). Effect of temperature and relative humidity on growth of Aspergillus and Penicillium spp. and biocontrol activity of Pseudomonas protegens AS15 against aflatoxigenic Aspergillus flavus in stored rice grains. Mycobiology, 46(3), 287–295.

[21] Schmidt-Heydt, M., Abdel-Hadi, A., Magan, N., et al. (2009). Complex regulation of the aflatoxin biosynthesis gene cluster of Aspergillus flavus in relation to various combinations of water activity and temperature. International Journal of Food Microbiology, 135, 231–237.

[22] Kumar, M., Kumar, H., Topno, R. K., & Kumar, J. (2019). Analysis of impact of anaerobic condition on the aflatoxin production in Aspergillus parasiticus Speare. Agricultural Science Digest-A Research Journal, 39(1), 75–78.

[23] Matsushima, K., Yashiro, K., Hanya, Y., Abe, K., Yabe, K., & Hamasaki, T. (2001). Absence of aflatoxin biosynthesis in koji mold (Aspergillus sojae). Applied Microbiology and Biotechnology, 55, 771–776.

[24] Awuchi, C. G., Ondari, E. N., Ogbonna, C. U., Upadhyay, A. K., Baran, K., Okpala, C. O. R., … Guiné, R. P. (2021). Mycotoxins affecting animals, foods, humans, and plants: Types, occurrence, toxicities, action mechanisms, prevention, and detoxification strategies—A revisit. Foods, 10(6), 1279.

[25] Cary, J. W., Gilbert, M. K., Lebar, M. D., Majumdar, R., & Calvo, A. M. (2018). Aspergillus flavus secondary metabolites: More than just aflatoxins. Food Safety, 6(1), 7–32.

[26] Pisoschi, A. M., Iordache, F., Stanca, L., Petcu, A. I., Purdoiu, L., Geicu, O. I., … Serban, A. I. (2023). Comprehensive overview and critical perspective on the

analytical techniques applied to aflatoxin determination–A review paper. Microchemical Journal, 191, 108770.

[27] Mallakian, S., Rezanezhad, R., Jalali, M., & Ghobadi, F. (2017). The effect of ozone gas on destruction and detoxification of aflatoxin. Bulletin de la Société Royale des Sciences de Liège, 86(1), 1–6.

[28] Lalah, J. O., Omwoma, S., & Orony, D. A. (2019). Aflatoxin B1: Chemistry, environmental and diet sources and potential exposure in human in Kenya. Aflatoxin B1 occurrence, detection and toxicological effects, 1–33.

[29] Zhang, K., & Banerjee, K. (2020). A review: Sample preparation and chromatographic technologies for detection of aflatoxins in foods. Toxins, 12(9), 539.

[30] Kutasi, K., Recek, N., Zaplotnik, R., Mozetič, M., Krajnc, M., Gselman, P., & Primc, G. (2021). Approaches to inactivating aflatoxins—a review and challenges. International Journal of Molecular Sciences, 22(24), 13322.

[31] Kumar, P., Mahato, D. K., Kamle, M., Mohanta, T. K., & Kang, S. G. (2017). Aflatoxins: A global concern for food safety, human health and their management. Frontiers in Microbiology, 7, 2170.

[32] Danesh, N. M., Bostan, H. B., Abnous, K., Ramezani, M., Youssefi, K., Taghdisi, S. M., & Karimi, G. (2018). Ultrasensitive detection of aflatoxin B1 and its major metabolite aflatoxin M1 using aptasensors: A review. TrAC Trends in Analytical Chemistry, 99, 117–128.

[33] Bernáldez, V., Cordoba, J. J., Magan, N., Peromingo, B., & Rodríguez, A. (2017). The influence of ecophysiological factors on growth, aflR gene expression and aflatoxin B1 production by a type strain of Aspergillus flavus. LWT - Food Science and Technology, 83, 283–291. https://doi.org/10.1016/j.lwt.2017.05.030

[34] Gizachew, D., Chang, C. H., Szonyi, B., De La Torre, S., & Ting, W. E. (2019). Aflatoxin B1 (AFB1) production by Aspergillus flavus and Aspergillus parasiticus on ground Nyjer seeds: The effect of water activity and temperature. International Journal of Food Microbiology, 2(296), 8–13. https://doi.org/10.1016/j.ijfoodmicro.2019.02.017

[35] Cinar Danso, J. K., Mbata, G. N., & Holton, R. L. (2024). Preharvest insect pests of peanuts and associated aflatoxin contaminants in Georgia, USA. Journal of Economic Entomology, 117(3), 993–1000.

[36] Nugraha, A., Khotimah, K., & Rietjens, I. M. (2018). Risk assessment of aflatoxin B1 exposure from maize and peanut consumption in Indonesia using the margin of exposure and liver cancer risk estimation approaches. Food and Chemical Toxicology, 113, 134–144.

[37] Panel, E. C., Schrenk, D., Bignami, M., Bodin, L., Chipman, J. K., Del Mazo, J., ... & Wallace, H. (2020). Risk assessment of aflatoxins in food.

[38] Boadu, R. O., Dankyi, E., Apalangya, V. A., & Osei-Safo, D. (2024). Aflatoxins in maize and groundnuts on markets in Accra and consumers risk. Food Additives & Contaminants: Part B, 1–10.

[39] Nadira, A. F., Rosita, J., Norhaizan, M., & Redzwan, S. M. (2017). Screening of aflatoxin M1 occurrence in selected milk and dairy products in Terengganu, Malaysia. Food Control, 73, 209–214. https://doi.org/10.1016/j.foodcont.2016.08.004

[40] Zhao, Y., Wang, Q., Huang, J., Ma, L., Chen, Z., & Wang, F. (2018). Aflatoxin B1 and sterigmatocystin in wheat and wheat products from supermarkets in China. Food Additives & Contaminants: Part B, 11(1), 9–14. https://doi.org/10.1080/19393210.2017.1388295

[41] Jeong, S. E., Chung, S. H., & Hong, S.-Y. (2019). Natural occurrence of aflatoxins and ochratoxin A in meju and soybean paste produced in South Korea. Applied Biological Chemistry, 62(1), 65. https://doi.org/10.1186/s13765-019-0472-y

[42] Kujbida, P., Maia, P. P., Araújo, A. N. d., Mendes, L. D., Oliveira, M. L. d., Silva-Rocha, W. P., Queiroz de Brito, G., Chaves, G., & Martins, I. (2019). Risk assessment of the occurrence of aflatoxin and fungi in peanuts and cashew nuts. Brazilian Journal of Pharmaceutical Sciences, 55. https://doi.org/10.1590/s2175-97902019000118135

[43] Demirhan, B., & Demirhan, B. (2021). The investigation of mycotoxins and Enterobacteriaceae of cereal-based baby foods marketed in Turkey. Foods, 10(12),

3040. https://doi.org/10.3390/foods10123040

[44] Ismaiel, A. A., Tharwat, N. A., Sayed, M. A., & Gameh, S. A. (2020). Two-year survey on the seasonal incidence of aflatoxin M1 in traditional dairy products in Egypt. Journal of Food Science and Technology, 1–8. https://doi.org/10.1007/s13197-020-04254-3

[45] Jeswal, P., & Kumar, D. (2015). Natural occurrence of toxigenic mycoflora and ochratoxin A & aflatoxins in commonly used spices from Bihar state (India). Journal of Environmental Science, Toxicology and Food Technology, 9(2), 50–55. https://doi.org/10.1155/2015/242486

[46] Namulawa, V. T., Mutiga, S., Musimbi, F., Akello, S., Ngángá, F., Kago, L., Kyallo, M., Harvey, J., & Ghimire, S. (2020). Assessment of fungal contamination in fish feed from the Lake Victoria Basin, Uganda. Toxins, 12, 233.

[47] Iswarawanti, D. N., Masloman, T. P. P., & HS, D. H. D. (2024). Exposure and knowledge on peanut aflatoxin B1 among urban consumer in Jakarta, Indonesia. AcTion: Aceh Nutrition Journal, 9(3), 559–567.

[48] Ahmed, U. A., & Beshah, A. (2024). Aflatoxicosis in dairy cow: A review. Mathews Journal of Veterinary Science, 8(1), 1–10.

[49] Tibebe, D., Kassaw, M., Mulugeta, M., Kassa, Y., Moges, Z., Yenealem, D., ... & Sheferaw, H. (2024). Assessment of aflatoxin contamination in roasted peanut samples from Gondar City, Ethiopia: Risk evaluation and health implications.

[50] Yan, T., Zhang, Z., Zhang, Q., Tang, X., Wang, D., Hu, X., ... & Li, P. (2020). Simultaneous determination for A. flavus–metabolizing mycotoxins by time-resolved fluorescent microbead or gold-enabling test strip in agricultural products based on monoclonal antibodies. Microchimica Acta, 187, 1–8.

[51] Jubeen, F., Batool, A., Naz, I., Sehar, S., Sadia, H., Hayat, A., & Kazi, M. (2024). Mycotoxins detection in food using advanced, sensitive and robust electrochemical platform of sensors: A review. Sensors and Actuators A: Physical, 115045.

[52] Liu, S., Jiang, S., Yao, Z., & Liu, M. (2023). Aflatoxin detection technologies: Recent advances and future prospects. Environmental Science and Pollution Research, 30(33), 79627–79653.

[53] Ouakhssase, A., Chahid, A., Choubbane, H., Aitmazirt, A., & Addi, E. A. (2019). Optimization and validation of a liquid chromatography/tandem mass spectrometry (LC-MS/MS) method for the determination of aflatoxins in maize. Heliyon, 5(5), e01660.

[54] Daliri, A., Shams-Ghahfarokhi, M., & Razzaghi-Abyaneh, M. (2023). Detection of Aflatoxin B1-producing Aspergillus flavus strains from pistachio orchards soil in Iran by multiplex polymerase chain reaction method. Current Medical Mycology, 9(3), 1.

[55] Yilmaz, S., & Bag, H. (2022). Aflatoxin B1: Mechanism, oxidative stress and effects on animal health. Journal of Animal Biology and Veterinary, 2, 1–16.

[56] Cao, W., Yu, P., Yang, K., & Cao, D. (2022). Aflatoxin B1: Metabolism, toxicology, and its involvement in oxidative stress and cancer development. Toxicology Mechanisms and Methods, 32(6), 395–419.

[57] Mgandu, F. A., Mirau, S., Nyerere, N., Mbega, E., & Chirove, F. (2024). Mathematical model to assess the impacts of aflatoxin contamination in crops, livestock and humans. Scientific African, 23, e01980.

[58] Karaca, A., Yilmaz, S., Kaya, E., & Altun, S. (2021). The effect of lycopene on hepatotoxicity of aflatoxin B1 in rats. Archives of Physiology and Biochemistry, 127, 429–436.

[59] McMillan, A., Renaud, J. B., Burgess, K. M. N., Orimadegun, A. E., Akinyinka, O. O., Allen, S. J., Miller, J. D., Reid, G., & Sumarah, M. W. (2018). Aflatoxin exposure in Nigerian children with severe acute malnutrition. Food and Chemical Toxicology, 111, 356–362. https://doi.org/10.1016/j.fct.2017.11.030

[60] Güç, İ., Yalçin, E., Çavuşoğlu, K., & Acar, A. (2022). Toxicity mechanisms of aflatoxin M1 assisted with molecular docking and the toxicity-limiting role of trans-resveratrol. Scientific Reports, 12(1), 14471.

[61] Dhakal, A., Hashmi, M. F., & Sbar, E. (2023, February 15). Aflatoxin toxicity. In StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing.

https://www.ncbi.nlm.nih.gov/books/NBK557781/

[62] Sharma, R. K., & Parisi, S. (2017). Aflatoxins in Indian food products. In Toxins and Contaminants in Indian Food Products (pp. 13–30). Springer, Cham. https://doi.org/10.1007/978-3-319-48049-7_2

[63] Chinaza, G. A., Erick, N. O., Hannington, T., Victory, S. I., & Ikechukwu, O. A. (2021). Aflatoxin B1 production, toxicity, mechanism of carcinogenicity, risk management, and regulations. Archives of Animal and Poultry Science, 1, 555–568.

[64] Marchese, S., Polo, A., Ariano, A., Velotto, S., Costantini, S., & Severino, L. (2018). Aflatoxin B1 and M1: Biological properties and their involvement in cancer development. Toxins, 10(6), 214. https://doi.org/10.3390/toxins10060214

[65] 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, 940–948.

[66] Loi, M., Renaud, J. B., Rosini, E., Pollegioni, L., Vignali, E., Haidukowski, M., Sumarah, M. W., Logrieco, A. F., & Mul, G. (2020). Enzymatic transformation of aflatoxin B1 by Rh_DypB peroxidase and characterization of the reaction products. Chemosphere, 250, 126296.

[67] Jailili, M., & Jinap, S. (2012). Role of sodium hydrosulphite and pressure on the reduction of aflatoxins and ochratoxin A in black pepper. Food Control, 27, 11–15.

[68] Hassan, F. F., & Hussein, H. Z. (2017). Detection of aflatoxin M1 in pasteurized canned milk and using of UV radiation for detoxification. International Journal of Advanced Chemical Engineering and Biological Sciences, 4, 130–133.

[69] Mohamed, N. F., El-Dine, R. S. S., Kot, M. A. M., & Saber, A. (2015). Assessing the possible effect of gamma irradiation on the reduction of aflatoxin B1, and on the moisture content in some cereal grains. American Journal of Biomedical Sciences, 7, 33–39.

[70] Mtega, M. M., Mgina, C. A., Kaale, E., Sempombe, S., & Kilulya, K. F. (2020). Occurrence of aflatoxins in maize and maize products from selected locations of Tanzania and the effects of cooking preparation processes on toxin levels. Tanzania Journal of Science, 46, 407–418.

[71] Matumba, L., Van Poucke, C., Ediage, E. N., Jacobs, B., & De Saeger, S. (2015). Effectiveness of hand sorting, flotation/washing, dehulling and combinations thereof on the decontamination of mycotoxin-contaminated white maize. Food Additives and Contaminants: Part A, 32, 960–969.

[72] Azam, K., Akhtar, S., Gong, Y. Y., Routledge, M. N., Ismail, A., Oliveira, C. A. F., Iqbal, S. Z., & Ali, H. (2021). Evaluation of the impact of activated carbon-based filtration system on the concentration of aflatoxins and selected heavy metals in roasted coffee. Food Control, 121, 107583.

[73] Peña-Rodas, O., Martinez-Lopez, R., & Hernandez-Rauda, R. (2018). Occurrence of aflatoxin M1 in cow milk in El Salvador: Results from a two-year survey. Toxicology Reports, 5, 671–678.

[74] Hamad, G. M., Zahran, E., & Hafez, E. E. (2017). The efficacy of bacteria and yeast strain and their combination to bind aflatoxin B1 and B2 in artificially contaminated infant food. Journal of Food Safety, 37, e12365.

[75] Ismail, A., Riaz, M., Akhtar, S., Yoo, S. H., Park, S., Abid, M., & Ahmad, Z. (2017). Seasonal variation of aflatoxin B1 content in dairy feed. Journal of Animal Feed Science, 26, 33–37.

[76] Bovo, F., Corassin, C. H., Rosim, R. E., & Oliveira, C. A. F. (2009). Efficiency of lactic acid bacteria strains for decontamination of aflatoxin M1 in phosphate buffer saline solution and in skimmed milk. Food and Bioprocess Technology, 6, 2230–2234.

[77] Bunny, S. M., Umar, A., Bhatti, H. S., & Honey, S. F. (2024). Aflatoxin risk in the era of climatic change-a comprehensive review. CABI Agriculture and Bioscience, 5(1), 1-13.

[78] Guan, Y., Chen, J., Nepovimova, E., Long, M., Wu, W., & Kuca, K. (2021). Aflatoxin Detoxification Using Microorganisms and Enzymes. Toxins, 13, 46.

[79] Eiri, A., Niknejad, F., & Ardebili, A. (2022). Detoxification of AFB1 by Yeasts Isolates from Kefir and Traditional Kefir-

Like Products. Medical Laboratory Journal, 16(4), 20-25.

[80] Adeniji, A. A., Loots, D. T., & Babalola, O. O. (2019). Bacillus velezensis: Phylogeny, Useful Applications, and Avenues for Exploitation. Applied Microbiology and Biotechnology, 103, 3669–3682.

[81] Wang, L., Wu, J., Liu, Z., Yutao, S., Jinqiu, L., Xiaofan, H., Peiqiang, M., Fengru, D., & Yiqun, D. (2019). Aflatoxin B1 degradation and detoxification by Escherichia coli CG1061 isolated from Chicken Cecum. Frontiers in Pharmacology, 9, 1548.

[82] 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 B1. Toxins, 6, 3157–3172.

[83] Suresh, G., Cabezudo, I., Pulicharla, R., Cuprys, A., Rouissi, T., & Brar, S. K. (2020). Biodegradation of aflatoxin B1 with cell-free extracts of Trametes versicolor and Bacillus subtilis. Research in Veterinary Science, 133, 85–91.

[84] Wang, Y., Jiang, L., Zhang, Y., Ran, R., Meng, X., & Liu, S. (2023). Research advances in the degradation of aflatoxin by lactic acid bacteria. Journal of Venomous Animals and Toxins including Tropical Diseases, 29, e20230029.

[85] Taheur, F. B., Fedhila, K., Chaieb, K., Kouidhi, B., Bakhrouf, A., & Abrunhosa, L. (2017). Adsorption of aflatoxin B1, zearalenone and ochratoxin A by microorganisms isolated from Kefir grains. International Journal of Food Microbiology, 251, 1–7.

[86] Taheur, F. B., Mansour, C., Jeddou, K. B., Machreki, Y., Kouidhi, B., Abdulhakim, J. A., & Chaieb, K. (2020). Aflatoxin B1 Degradation by Microorganisms Isolated from Kombucha Culture. Toxicon, 179, 76–83.

[87] Watanakij, N., Visessanguan, W., & Petchkongkaew, A. (2020). Aflatoxin B1-degrading activity from Bacillus subtilis BCC 42005 isolated from fermented cereal products. Food Additives & Contaminants: Part A, 37(9), 1579–1589.

[88] Qiu, T., Wang, H., Yang, Y., Yu, J., Ji, J., Sun, J., Zhang, S., & Sun, X. (2021). Exploration of biodegradation mechanism by AFB1-degrading strain Aspergillus niger FS10 and its Metabolic Feedback. Food Control, 121, 107609.

[89] Li, J., Huang, J., Jin, Y., Wu, C., Shen, D., Zhang, S., & Zhou, R. (2018). Aflatoxin B1 degradation by salt tolerant Tetragenococcus halophilus CGMCC3792. Food and Chemical Toxicology, 121, 430–436.

[90] Shetty, P. H., Hald, B., & Jespersen, L. (2007). Surface binding of aflatoxin B1 by Saccharomyces cerevisiae strains with potential decontaminating abilities in indigenous fermented foods. International Journal of Food Microbiology, 113(1), 41–46.

[91] Kumar, V., Ahluwalia, V., Saran, S., Kumar, J., Patel, A. K., & Singhania, R. R. (2021). Recent developments on solid-state fermentation for production of microbial secondary metabolites: Challenges and solutions. Bioresource Technology, 323, 124566.

[92] 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, 621–625.

[93] Alberts, J. F., Gelderblom, W. C. A., Botha, A., & Van Zyl, W. H. (2009). Degradation of aflatoxin B1 by fungal laccase enzymes. International Journal of Food Microbiology, 135, 47–52.

[94] Zaid, A. M. A. (2017). Biodegradation of aflatoxin by peroxidase enzyme produced by local isolate of Pseudomonas sp. International Journal of Scientific Research and Management, 5, 7456–7467.

[95] Li, C. H., Li, W. Y., Hsu, I. N., Liao, Y. Y., Yang, C. Y., Taylor, M. C., Liu, Y. F., Huang, W. H., Chang, H. H., Huang, H. L., et al. (2019). Recombinant aflatoxin-degrading F420H2-dependent reductase from Mycobacterium smegmatis protects mammalian cells from aflatoxin toxicity. Toxins, 11, 259.

[96] Yehia, R. S. (2014). Aflatoxin Detoxification by Manganese Peroxidase Purified from Pleurotus ostreatus. Brazilian Journal of Microbiology, 45, 127–134.

[97] Pereyra, M. G., Martínez, M. P., & Cavaglieri, L. R. (2019). Presence of aiiA homologue genes encoding for N-acyl homoserine lactone-degrading enzyme in aflatoxin B1-decontaminating Bacillus strains with potential use as feed additives. Food and Chemical Toxicology, 124, 316–323.

[98] Tang, X., Cai, Y. F., Yu, X. M., & Zhou, W. W. (2023). Detoxification of aflatoxin B1 by Bacillus aryabhattai through conversion of double bond in terminal furan. Journal of Applied Microbiology, 134(9), lxad192.
[99] Wang, J., Ogata, M., Hirai, H., & Kawagishi, H. (2011). Detoxification of aflatoxin B1 by manganese peroxidase from the white-rot fungus Phanerochaete sordida YK-624. FEMS Microbiology Letters, 314(2), 164–169.
[100] Guo, Y., Qin, X., Tang, Y., Ma, Q., Zhang, J., & Zhao, L. (2020). CotA laccase, a novel Aflatoxin Oxidase from Bacillus licheniformis, Transforms Aflatoxin B1 to aflatoxin Q1 and epi-aflatoxin Q1. Food Chemistry, 325, 126877.
[101] Borgomano, S. (2015). Degradation of selected microbial aflatoxins from Aspergillus parasiticus by partial purified laccase from Coriolus hirsutus. PhD Dissertation, Institut National de la Recherche Scientifique, Université du Québec, Quebec City, QC, Canada.
[102] Gong, A., Song, M., & Zhang, J. (2024). Current Strategies in Controlling Aspergillus flavus and Aflatoxins in Grains during Storage: A Review. Sustainability, 16(8), 3171.
[103] Leslie, J. F., Bandyopadhyay, R., & Visconti, A. (Eds.). (2008). Mycotoxins: Detection Methods, Management, Public Health and Agricultural Trade. CABI.
[104] Vural, B. M., & Akgüngör, E. S. (2019). Quantifying the trade and welfare effects of EU Aflatoxin Regulations on the dried fruit industry. German Journal of Agricultural Economics (GJAE), 68(2), 99–117.
[105] Purnomo, J., Rahmianna, A. A., Ginting, E., Suratman, Elisabeth, D. A. A., & Sundari, T. (2023). The Pod Performance and Pod Yield of Peanut (Arachis hypogaea L.) Genotypes Grown Under Wet Condition and Their Microbial Quality Under Different Curing Times. Applied Ecology and Environmental Research, 21(2), 1157–1183.
[106] Khachatryan, N., Zeddies, J., Schüle, H., & Khachatryan, A. (2005). Quantification of the economic impact of EU aflatoxins standards on developing and transition countries. Department for International Agricultural Trade and Food Security, Department for Analysis, Planning and Organization of Agricultural Production, Department for Computer Applications and Business Management in Agriculture University of Hohenheim, Stuttgart, Germany.
[107] Chandra, P. (2021). Aflatoxins: Food safety, human health hazards and their prevention. In Aflatoxins-Occurrence, Detoxification, Determination and Health Risks. IntechOpen.
[108] Rahman, M. A. H., Selamat, J., Shaari, K., Ahmad, S., & Samsudin, N. I. P. (2024). Extrolites from Non-Aflatoxigenic Aspergillus flavus: Potentials and Challenges as Emerging Control Strategy against Aspergillus flavus Infection and Aflatoxin Contamination. Current Opinion in Food Science, 101214.
[109] Shabeer, S., Asad, S., Jamal, A., & Ali, A. (2022). Aflatoxin contamination, its impact and management strategies: an updated review. Toxins, 14(5), 307.
[110] Kaale, L., Kimanya, M., Macha, I., & Mlalila, N. (2021). Aflatoxin contamination and recommendations to improve its control: A review. World Mycotoxin Journal, 14, 27–40.
[111] Fortin, N. D. (2023). Global governance of food safety: the role of the FAO, WHO, and Codex Alimentarius in regulatory harmonization. In Research Handbook on International Food Law (pp. 227–242). Edward Elgar Publishing.
[112] European Food Safety Authority (EFSA). (2020). Outcome of a public consultation on the draft risk assessment of aflatoxins in food. EFSA Journal, 17(3), 1798E.
[113] Cai, Y., McLaughlin, M., & Zhang, K. (2020). Advancing the FDA/Office of Regulatory Affairs Mycotoxin Program: new analytical method approaches to addressing needs and challenges. Journal of AOAC International, 103(3), 705–709.
[114] Singh, N. A., Tehri, N., Vashishth, A., & Kumar, P. (2023). Nano-Biosensors for the Monitoring of Toxic Contaminants in Food and its Products. In Mycotoxins in Food and Feed (pp. 429–448). CRC Press.
[115] Liu, Y. (2022). Approaches to reduce Aspergillus flavus and aflatoxin contamination through utilization of agricultural by-products.
[116] Wang, Y., Yang, L., Xu, J., Xin, F., & Jiang, L. (2023). Applications of synthetic microbial consortia in biological control of mycotoxins and fungi. Current Opinion in Food Science, 53, 101074.

[117] Fang, J., Sheng, L., Ye, Y., Ji, J., Sun, J., Zhang, Y., & Sun, X. (2025). Recent advances in biosynthesis of mycotoxin-degrading enzymes and their applications in food and feed. Critical Reviews in Food Science and Nutrition, 65(8), 1465–1481.
[118] Zhao, Z., Lu, M., Wang, N., Li, Y., Zhao, L., Zhang, Q., & Ma, L. (2023). Nanomaterials-assisted CRISPR/Cas detection for food safety: Advances, challenges and future prospects. TrAC Trends in Analytical Chemistry, 167, 117269.