Food Bioscience 73 (2025) 107667

Contents lists available at ScienceDirect

Food Bioscience

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

Prevention and detoxification of mycotoxins in food and feed: A review

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ARTICLE INFO

Keywords:
Mycotoxin
Detoxification
Control
Reduction
Biocontrol
Adsorbents
Enzymes

ABSTRACT

Mycotoxins are toxic secondary metabolites produced by various species of fungi, including mainly *Fusarium* spp., *Aspergillus* spp., and *Penicillium* spp., which are found globally in different foods and animal feed. These substances present significant health risks to both humans and animals due to their carcinogenic, genotoxic, teratogenic, nephrotoxic, and hepatotoxic properties. These toxins contaminate food and feed products during the harvesting and storage process, affecting up to 50 % of the total and causing significant economic losses. The financial impact of this issue includes not only the costs associated with disposing of contaminated food but also a reduction in overall food productivity. The main types of mycotoxins that pose serious risks to both human and animal health include aflatoxins, fumonisins, ochratoxins, zearalenone, trichothecenes, ergot alkaloids and patulin. The impact of physical and chemical methods on food quality, their environmental toxicity, cost implications, and potential for leaving residues, as well as concerns about the consistency of production with biological processes, are among the limitations. Advances in biotechnology are expected to offer the greatest potential for future improvements. This review aims to highlight the latest techniques used to reduce or eliminate mycotoxins in food and feed materials using physical, chemical, and biological methods.

Abbreviations and definitions used in this review

Abbrevition	Definition
A. flavus	*Aspergillus flavus*
A. paraciticus	*Aspergillus paraciticus*
A. nomius	*Aspergillus nomius*
A. niger	*Aspergillus niger*
A. ochraceus	*Aspergillus ochraceus*
AFB1	Aflatoxin B1
AFB2	Aflatoxin B2
AFG1	Aflatoxin G1
AFG2	Aflatoxin G2
AFM1	Aflatoxin M1
AFQ1	Aflatoxin Q1
OTA	Ochratoxin A
OTα	Ochratoxin α
FB1	Fumonisin 1
FB2	Fumonisin 2
HFB1	Hydrolyzed Fumonisin B1
pHFB1	Partially Hydrolyzed Fumonisin B1
ZEA	Zearalenone
DON	Deoxynivalenol
IARC	International Agency for Research on Cancer
EFSA	European Food Safety Authority
cAMP	Cyclic adenosine monophospate
sTAR	Steroidogenic acute regulatory protein
IGF-1	Insulin-like growth factor
UV	Ultraviolet light
UHT	Ultra-high temperature
HACCP	Hazard analysis and critical control points
HSCAS	Hydrated sodium calcium aluminosilicates
LAB	Lactic acid bacteria
ROS	Reactive oxygen species
EU	European Union
WHO	World Health Organization
HPLC	High performance liquid chromatography
LC-MS/MS	Liquid chromatography–mass spectrometry
ELISA	Enzyme-linked immunosorbent assay
NIS	Near infrared spectroscopy
LFI	Lateral flow immunoassay
AAS	Atomic absorption spectrophotometry
HepG2	Human liver carcinoma cells

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https://doi.org/10.1016/j.fbio.2025.107667
Received 1 July 2025; Received in revised form 23 September 2025; Accepted 25 September 2025
Available online 26 September 2025

1. Introduction

The term "mycotoxin" is a combination of the Greek words "*Mykis*", which means mould, and "*Toxicon*", which means poison in Latin (Bennett & Klich, 2003). Mycotoxins are defined as secondary metabolites that are produced mainly by fungi belonging to the species *Aspergillus* spp., *Penicillium* spp., and *Fusarium* spp. (Akande et al., 2006). The most extensively studied and globally relevant mycotoxins include **aflatoxins, ochratoxin A, fumonisins, deoxynivalenol, and zearalenone (**Bennett & Klich, 2003; Gruber-Dorninger et al., 2019). The main mycotoxins, products, effects and chemical structures are presented in Table 1. These toxins have the capacity to contaminate a wide range of feed and food. It is estimated that 25 %–50 % per cent of cereal production is affected by mycotoxins, with 5 %–10 % per cent contaminated at high concentrations (Abrunhosa et al., 2016; Haque et al., 2020). Climate change directly affects changes in precipitation, relative humidity, and temperature, while indirectly affecting wind-driven fungal spore dispersal, insect attacks, and changes in grains (Liu & Van der Fels-Klerx, 2021). Consequently, future increases in temperatures and CO_2 concentrations are projected to lead to increased mycotoxin contamination (Leggieri et al., 2021). Consumption of mycotoxin-contaminated feed and nutrients can cause economic losses as a result of directly affecting animal health. It indirectly affects public health through residues in products such as meat, milk and eggs obtained from animals consuming contaminated feed and food (Becker-Algeri et al., 2016; Muzaffar et al., 2025). In addition to well-known mycotoxins, recent attention has also focused on emerging mycotoxins, including enniatins, fusaproliferin, and beauvericin. Although these mycotoxins are also known to contaminate food and feed, little data is available (Gruber-Dorninger et al., 2017; Tolosa et al., 2021).

Feed and nutrients are vulnerable to fungal infestation and can become contaminated with mycotoxins when conditions favour fungal growth, particularly influenced by temperature and humidity during storage, blending, transport, and processing phases (Joubrane et al., 2020; Perdoncini et al., 2019). There is no definitive cure for mycotoxin-induced toxicity. Therefore, prevention measures must be implemented to reduce the formation of mycotoxins and avoid contamination. Preventative strategies exist both pre-harvest and post-harvest. Additionally, failure to maintain proper conditions (e.g., humidity, temperature, oxygen, and time) can significantly reduce mycotoxin production (Boudergue et al., 2009).

Maximum limits within which mycotoxin levels can be found in food and feed have been set by leading authorities (EFSA, 2004; EU, 2023). It is estimated that more than 500 million people are exposed to mycotoxins above tolerable limits (WHO, 2023; Zinedine et al., 2025). Exceeding the recommended limits has been shown to cause acute and chronic hepatotoxic, nephrotoxic, immunosuppressive, and carcinogenic effects in both humans and animals. The risk of these effects depends on the mycotoxin dose, the duration of exposure, and the simultaneous presence of multiple mycotoxins (Akande et al., 2006; IARC, 2023; Yiannikouris & Jouany, 2002).

Mycotoxins are detected using chromatographic methods (HPLC, LC-MS/MS), immunochemical methods (ELISA, LFI), and spectroscopic methods (NIS, AAS). Chromatographic methods are the most commonly used detection technologies and offer higher accuracy, selectivity, and sensitivity compared to other methods. However, cost, solvent consumption, and the need for well-trained personnel limit their use (Naeem et al., 2024).

Mycotoxins can be prevented from absorption from the digestive system after ingestion of mycotoxin-contaminated feed or food by reducing their adsorption by various adsorbents or detoxifying agents, or by converting them into less toxic substances. To reduce the severity of adverse effects such as decreased yield and immunosuppression caused by mycotoxin exposure, it is important to use substances that reduce the severity of these adverse effects (Jard et al., 2011; Shekhar et al., 2025).

Given the health impact and global importance of mycotoxins, detoxification strategies are needed. This review focuses on physical, chemical, biological and plant bioactive compounds approaches to reduce mycotoxin levels in food and feed. Particular attention is paid to their mechanisms of action, practical limitations and potential for industrial application. By critically evaluating both traditional and emerging detoxification methods, it is intended to provide an up-to-date overview that will inform risk management and guide future research directions.

1.1. Aflatoxins

They are highly lipophilic and heat-resistant compounds with a difurano-coumarin structure (Wild & Gong, 2010). They are produced by *Aspergillus* species, mainly *A. flavus, A. parasiticus and A. nomius.* There are 4 most common types. These are AFB1, AFB2, AFG1, AFG2. Under ultraviolet light, AFB1 and AFB2 give blue fluorescence and AFG1 and AFG2 give green fluorescence. It was found that a derivative of this toxin was present in the milk of animals consuming feed containing aflatoxin B, and because of its presence in milk, it was named Aflatoxin M, meaning milk toxin (Sweeney & Dobson, 1998).

Aflatoxins are a group of mycotoxins that pose significant concerns regarding human intoxication. AFB1 is the most potent toxin known for causing liver cancer. IARC classified aflatoxins as Group 1 carcinogens, indicating they are recognized as cancer-causing agents in humans (IARC, 2023). Maximum residue limits have been reported as 0.10–12 μg/kg for AFB1, 4–15 μg/kg for AFB2, AFG1, AFG2 and 0.025–0.050 μg/kg for AFM1 (EU, 2023). AFB1 is one of the most damaging and toxic aflatoxin types. It is formed in tropical places with very high temperatures and humidity. AFB1 reacts with components such as proteins and cell organelles and disrupts normal cellular functions. As a result, it can cause suppression of the immune system, and carcinogenic, teratogenic and mutagenic effects (da Silva et al., 2021). In both humans and animals, aflatoxins are associated with severe toxicological consequences, including liver cancer, immunosuppression (Massomo, 2020). Following epoxidation at the terminal furan ring, AFB1 produces ROS and creates oxidative stress and forms adducts with DNA in the liver via cytochrome P450 enzymes, leading to mutations that can cause carcinogenesis (Peles et al., 2019). Contamination of foods with aflatoxins before harvest is the main cause of post-harvest aflatoxin contamination, which results in a decrease in the quality of nutritional content (Agbetiameh et al., 2020). Versicolorin A was discovered as an early biomarker of contamination with aflatoxins in food and feedstuffs. his lead compound was reported to have a stronger cytotoxic effect than the same dose of AFB1 (Gauthier et al., 2020).

1.2. Ochratoxins

Ochratoxins are secondary metabolites formed by *Penicillium viridicatum, A. ochraceus, Penicillium expansum, Penicillium nidulans* and *Penicillium cyclopium.* There are three subtypes of ochratoxins, A, B, and C, among which OTA produces a particularly extreme toxicity (El Khoury and Atoui, 2010). They are isocoumarin derivatives and have a dihydroisocoumarin structure combined with phenylalanine. The presence of a chlorine atom affects the rate of biotransformation and elimination (Malir et al., 2016). OTA is formed by the growth of moulds in coffee beans, soya beans, cocoa beans, oats, maize, wine, dried beans, groundnuts and citrus fruits (Anli and Bayram, 2009; Nazareth et al., 2024). Maximum residue limits have been reported as 0.5–20 μg/kg for OTA (EU, 2023). Ochratoxins have potential adverse effects such as nephrotoxicity, carcinogenic effects, and immunosuppression by causing kidney damage (Pfohl-Leszkowicz & Manderville, 2007). They are also classified by IARC as a potent nephrocarcinogenic Group 2 B carcinogen (IARC, 2023). OTA can be found predominantly in meat products, which is a concern regarding access to safe food (Tolosa et al.,

Table 1
Major mycotoxin types, fungal producers, chemical structures and effects (structures generated from InChI code available on (https://pubchem.ncbi.nlm.nih.gov/) (accessed on August 28, 2025).

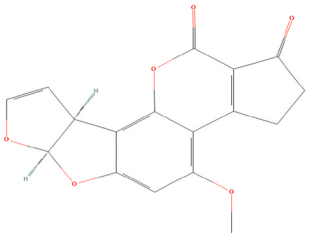
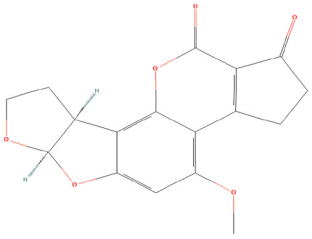
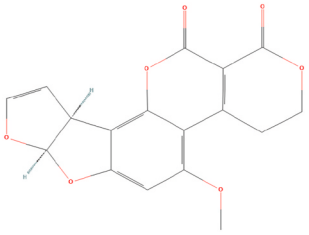
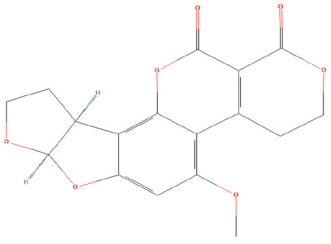
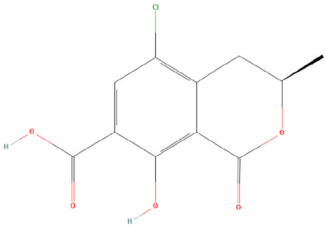
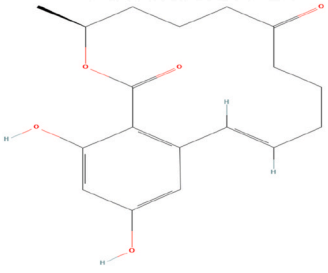
Mycotoxins	Fungal species	Effects	Chemical structures
AFB1	*A. flavus, A. parasiticus, A. nomius*	Hepatotoxic, carcinogenic, immunosuppressive	
AFB2			
AFG1			
AFG2			
OTA	*A. ochraceus, Penicillium verrucosum, Aspergillus carbonarius*	Nephrotoxic, potential carcinogenic, immunomodulatory, teratogenic, embryotoxic	
ZEA	*Fusarium graminearum, Fusarium culmorum, Fusarium crookwellense*	Estrogenic effect, reproductive disorders	

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Table 1 (*continued*)

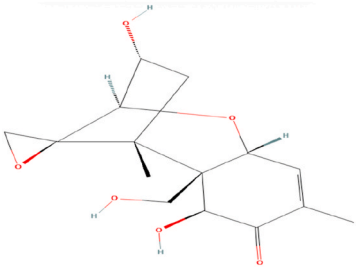
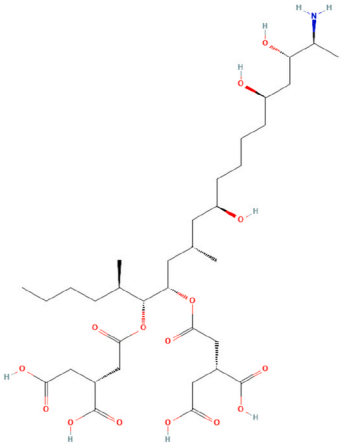
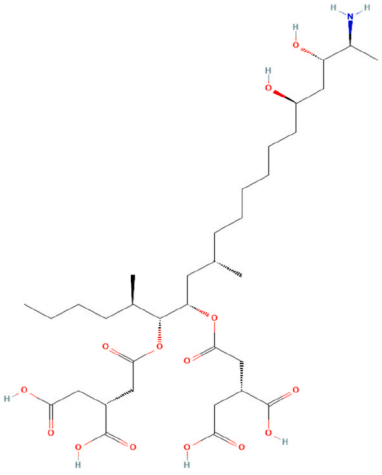
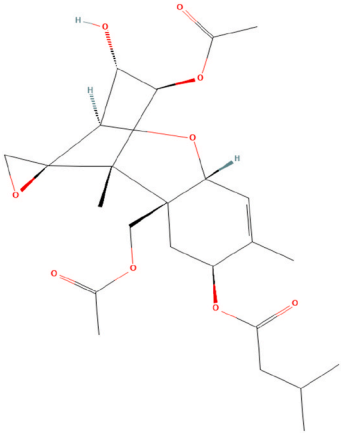
Mycotoxins	Fungal species	Effects	Chemical structures
DON	*Fusarium graminearum, Fusarium culmorum*	Growth retardation, ribotoxic stress, immunosuppression, immunomodulatory, damage to the intestinal epithelium	
FB1	*Fusarium verticillioides, Fusarium proliferatum*	Hepatotoxic, nephrotoxic, carcinogenic, damage to the sphingolipid metabolism	
FB2			
T-2	*Fusarium sporotrichioides, Fusarium poae*	Protein synthesis inhibitor, hematotoxic, immunosuppression, dermatoxic	

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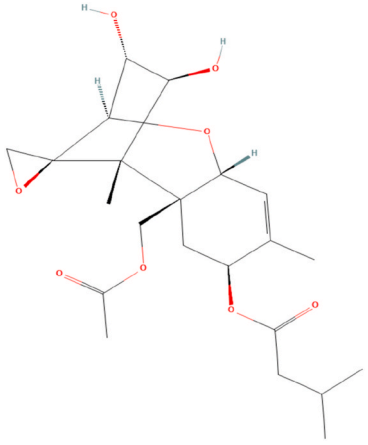
Table 1 (*continued*)

Mycotoxins	Fungal species	Effects	Chemical structures
HT-2			

2021). Monogastric species are more susceptible than ruminants due to differences in their detoxification mechanisms. Ruminants are able to detoxify OTα (Schrenk et al., 2023).

1.3. Fumonisins

Fumonisins are naturally occurring metabolites of different *Fusarium* fungi. Although different fumonisin species are known, FB1, FB2, Fumonisin B3, Fumonisin B4, Fumonisin A1, Fumonisin A2 and Fumonisin A3 are the main forms found in foods. Fumonisins were first discovered in 1988 (Gelderblom et al., 1991). It is one of the mycotoxin types that causes the most important contamination in maize, which is frequently used in feed consumed by humans and animals. When suitable environmental conditions are provided before harvest, their reproduction causes economic losses worldwide (Ariño et al., 2009; Munkvold et al., 2019). FB1 has a cytotoxic effect (apoptosis and necrosis) in mammalian cells and causes inhibition of sphingolipid biosynthesis (Chen et al., 2021; Gelderblom et al., 1991). Since sphingolipid metabolism is affected as a result of fumonisin exposure, it has been associated with cancer and neural tube defects in humans, pulmonary oedema in pigs and leukoencephalomalacia in horses. In addition, it causes liver and kidney damage, leading to hepatotoxicity and nephrotoxicity (Ashiq, 2015). Fumonisins have been classified as Group 2 B, meaning they are possibly carcinogenic to humans, by IARC (IARC, 2023). Maximum residue limits have been reported as 200–4.000 μg/kg for FB1 and FB2 (EU, 2023).

1.4. Zearalenones

ZEA is an estrogenic secondary metabolite containing a resorcylic acid lactone group produced by *Fusarium* species, especially *Fusarium graminearum* and *Fusarium culmorum* (Alshannaq & Yu, 2017). Resorcylic acid has a lactone structure and exhibits estrogenic activity by binding to estrogen receptors thanks to its phenolic hydroxyl groups (Zinedine et al., 2007). ZEA undergoes a reduction reaction in the liver via hydroxysteroid dehydrogenase enzymes, and as a result of this reaction, ZEA is converted into its reduced main metabolites, α-zearalenol and β-zearalenol. Although the concentration of ZEA decreases as a result of this reaction, the estrogenic effect increases because α-zearalenol has a higher binding affinity to estrogen receptors. After the reduction reaction, the reduced metabolites are conjugated by glucuronidation and sulphation and excreted in bile and urine (Marin et al., 2013; Molina-Molina et al., 2014; Zinedine et al., 2007). Consequently, these substances disrupt estrogen metabolism and compete with the body's estrogen at the binding sites of estrogen receptors. Accordingly, the alteration of normal physiological responses, even at low doses of ZEA, has been demonstrated to cause reproductive toxicity (Döll & Dänicke, 2011; Lo et al., 2021; Minervini and Dell'Aquila, 2008; Tiemann & Dänicke, 2007). Maximum residue limits have been reported as 20–350 μg/kg for ZEA (EU, 2023). Research has demonstrated that ZEA induces abnormal renal function and induces kidney damage by increasing oxidative stress and apoptosis (Ben Salem et al., 2015; Zhang et al., 2018). In addition to its toxic effects on the reproductive system, ZEA also has other toxic effects such as genetic toxicity, teratogenicity, immunosuppression, carcinogenicity and hepatotoxicity (Cai et al., 2024; Rogowska et al., 2019).

1.5. Trichothecenes

It is produced by several mould species, including *Fusarium* spp., *Stachybotrys* spp., *Myrothecium* spp., *Trichothecium* spp., *Trichoderma* spp., *Cephalosporium* spp., *Cylindrocarpon* spp., *Verticimonosporium* spp. and *Phomopsis* spp. (Milićević et al., 2010; Polak-Śliwińska & Paszczyk, 2021). More than 170 types of trichothecenes have been isolated. Although the chemical structures of these toxin groups are similar, they are divided into four groups according to the differences in the epoxy ring located at C_{12}-C_{13}. These are classified as Type A (T-2 toxin, HT-2 toxin, neosolaniol, diacetoxysirpenol, harzinum A), Type B (Deoxynivalenol, nivalenol), Type C (crotocin) and Type D (satratoxin G, satratoxin H, roridin A, verrucarin A) (Marin et al., 2013). T-2 toxin inhibits protein synthesis by binding to the peptidyl transferase enzyme of the 60 S ribosomal subunit due to its high affinity, causing inhibition of the enzyme (Doi et al., 2008). T-2 can inhibit the activation of the cAMP pathway, reducing the synthesis of steroid hormones, estradiol and progesterone, due to reduced production of StAR (Wu et al., 2015). As a result of chronic exposure, IGF-1 interferes with the signalling of the hormones insulin and leptin and severely slows growth in animals by suppressing growth hormones (Wan et al., 2015). DON produces serious adverse effects on rapidly proliferating cells and concurrently inhibits protein synthesis (You et al., 2021). During metabolism, DON associates with nuclear ribosomes, eliminates their functional structures by separating peptide bonds and chains, disrupts the active site of peptidyl transferase on the ribosomal 60 S subunits, and finally inhibits protein synthesis (Yao & Long, 2020). In addition, DON damages the function of the intestinal barrier by reducing the synthesis of tight junction proteins, resulting in reduced growth performance in animals. This toxin damages the intestinal barrier by reducing the synthesis of tight junctions in the intestinal epithelium. This directly causes a decrease in the growth performance of animals (Pinton & Oswald, 2014). Maximum residue limits have been reported as 200–1.750 μg/kg for DON (EU, 2023).

2. Mycotoxin control and reduction methods

It is possible to reduce the burden of mycotoxins found in food, feed and feedstuff through industrial processing or by using additives that eliminate or neutralize these toxins. An effective decontamination process involves destroying or neutralizing mycotoxins while avoiding the formation of toxic by-products. Additionally, these processes should preserve the nutritional value of the food and maintain the technological properties of the product (Bullerman & Bianchini, 2007).

All mycotoxins are highly stable substances and applying any physical or chemical treatment to them can change the nutritional value of the grain or significantly increase costs. For instance, while the use of ammonia or strong oxidising agents has been demonstrated to reduce contamination, there is also a risk that these agents may diminish the nutritional value of the feed. The most common method to reduce exposure to mycotoxins is through the incorporation of various mycotoxin-binding agents, or adsorbents. These adsorbents function by diminishing the adsorption of mycotoxins from the digestive tract, thereby constraining their distribution into the bloodstream and target organs. However, the efficacy of these agents is contingent upon their stability within the complex digestive system of animals, which allows bound toxins to be excreted through urine and faeces (Bullerman & Bianchini, 2007; Jouany, 2007). As indicated by the findings of the EFSA (2009) and Jard et al. (2011), the methods employed for mycotoxin control and reduction are illustrated in Fig. 1.

2.1. Physical control methods

A variety of practices can be employed to naturally remove mycotoxins. These include grading, classifying, and removing visibly affected parts of the produce. Physical processes used for mycotoxin decontamination encompass drying, washing, cleaning, separating, grinding, boiling, roasting, irradiation, extrusion, microwave heating, peeling, and the use of adsorbents. Additionally, implementing post-harvest preventive HACCP approaches can help address the issue of mycotoxin contamination (Sarrocco & Vannacci, 2018; Shi et al., 2018). Recent studies on the reduction of mycotoxins using physical control methods are summarized in Table 2.

2.1.1. Thermal treatment

Mycotoxins in feed and feed raw materials can be reduced by various processing techniques (Neme & Mohammed, 2017). In addition, since most mycotoxins are resistant to temperatures ranging from 80 to 120 °C, which are commonly used in traditional food processing methods (frying, boiling, baking, pasteurisation), a slight reduction in toxin levels can be observed. However, it is known that the reduction rate of aflatoxins varies between 50 % and 80 % during the extrusion process, as both the processing temperature and the moisture content of the granules are affected (Oliveira et al., 2013; Shanakhat et al., 2018). DON is heat-resistant at 120 °C, moderately resistant at 180 °C, and partially resistant at 210 °C (Bulder et al., 2011). Additionally, it has been reported that applying temperatures between 150 and 200 °C reduces the toxin content in AFB1-contaminated products by an average of 79 % and that products with high moisture content yield more effective results because the moisture content increases the effectiveness of the applied heat (Rushing & Selim, 2019).

Nixtamalization, a process that involves cooking in alkaline water, can effectively reduce the levels of fumonisin and aflatoxin in food products, provided that the cooking liquid is discarded. Some studies have shown that nixtamalization can decrease aflatoxin levels in alkali-cooked maize and tortillas (Moreno-Pedraza et al., 2015; Price & Jorgensen, 1985). The impact of alkaline additives on DON sensitivity was noted in both bakery production and noodle cooking processes (Farahany & Jinap, 2011). Additionally, other cooking methods such as baking, frying, and extrusion cooking of corn at high temperatures (above 190 °C) can also lower fumonisin concentrations in foods (Humpf & Voss, 2004). It was observed that the fumonisin content in maize semolina decreased by approximately 70 %–76 % after 5 min of roasting (Lešnik et al., 2008). During extrusion cooking of cereals, a 95 % reduction in the amount of aflatoxin and a 55 % reduction in the amount of DON were recorded. Extrusion cooking has been shown to reduce mycotoxin levels, with the effectiveness depending on various factors such as the type of extruder used, screw configuration, die design, initial mycotoxin concentration, barrel temperature, screw speed, moisture content of the raw material, and the addition of any additives (Castells et al., 2005; Kaushik, 2015). Reductions in aflatoxins and OTA levels have been reported following roasting in pistachios and sunlight drying in maize (Gillani et al., 2022; Jalili et al., 2020).

2.1.2. Non-thermal treatment

Food decontamination technologies such as irradiation, UV, electron beam, ultrasound, microwave irradiation, pulsed light, pulsed electric field, and cold plasma technologies are used as mycotoxin degradation methods (Adebo et al., 2021). Pulsed light technology involves the transmission of short-term, high-intensity light pulses across a broad spectrum (200–1000 nm), including infrared, visible light and UV.

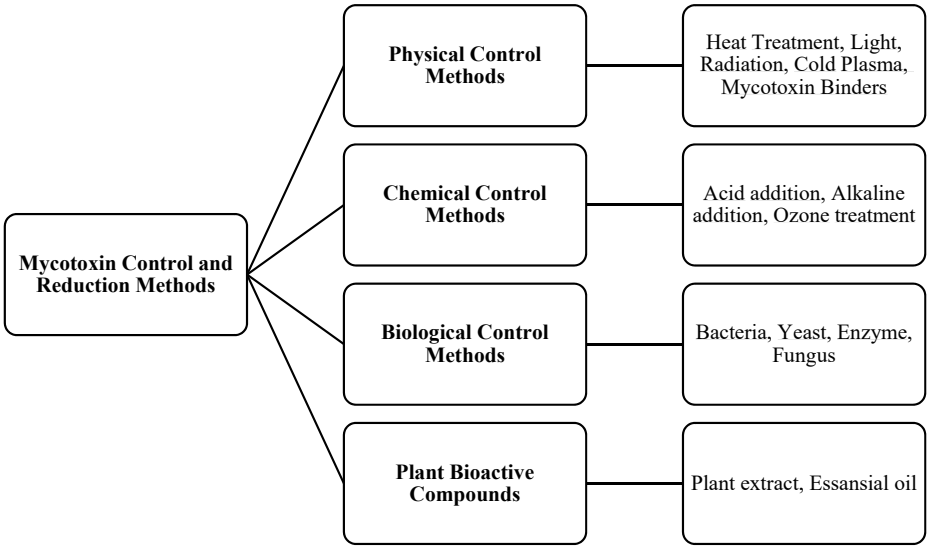


Fig. 1. Mycotoxin control and reduction methods.

Table 2
Mycotoxins removal percentage of physical treatment.

Physical Treatments	Target Mycotoxins	Effects	References
Sunlight treatment	AFB1	100 % reduction in 20 h	Gillani et al. (2022)
	Aflatoxins	100 % reduction in 20 h	
	OTA	100 % reduction in 20 h	
Roast	Aflatoxins, OTA	85.7 % reduction in 150 °C 50 min	Jalili et al. (2020)
Microwave radiation	Aflatoxins, OTA	72.5 % reduction in 10 min	
	AFB1	50.06 % reduction in 560 W 2 min	Chandravarnan et al. (2025)
	Aflatoxins	40 % reduction in 720 W 6 min	
	OTA	75.24 % reduction in 560 W 2 min	
	AFB1	29 % reduction in 120 s	Gillani et al. (2022)
	Aflatoxins	33 % reduction in 120 s	
	OTA	33 % reduction in 120 s	
Pulsed light irradiation	Aflatoxins	50.9 % reduction in 9,1 J/cm^2, 61 pulses, 20 s	Woldemariam et al. (2022)
	OTA	36.9 % reduction in 9,1 J/cm^2, 61 pulses, 20 s	
	AFB1	67.2 % reduction in 9,1 J/cm^2, 61 pulses, 20 s	
		72.09 % degradation in 40 flashes at 100 μg/mL	Qi et al. (2023)
	AFB2	73.65 % degradation in 40 flashes at 100 μg/mL	
	AFG1	57.06 % degradation in 40 flashes at 100 μg/mL	
	AFG2	69.69 % degradation in 40 flashes at 100 μg/mL	
	OTA	95.29 % degradation and reduction of toxic effects, oxidative stress parameters in mice	Wang et al. (2022)
High-intensity pulsed light		62.50 % reduction of 12 J	Ertek et al. (2024)
UV-A	AFB1	78.2 % reduction at 836 mJ/cm^2	Kurup et al. (2022)
	AFM1	65.7 % reduction at 857 mJ/cm^2	
UV-C	AFB1	44.33 % reduction in 15 mW/cm^2 in 30 min	Chandravarnan et al. (2025)
	Aflatoxins	31.09 % reduction in 15 mW/cm^2 in 30 min	
	OTA	59.96 % reduction in 15 mW/cm^2 in 30 min	
	AFM1	50 % reduction in 20 min	Nguyen, Palmer, Loo, et al. (2022)
	AFB1	100 % reduction in 12 h	Gillani et al. (2022)
	Aflatoxins	100 % reduction in 12 h	
	OTA	100 % reduction in 12 h	
Gamma ray irradiation	AFB1	59 % degradation in 10 kGy	Ben Amara et al. (2022)
	OTA	32 % degradation in 10 kGy	
Pulsed electric fields	AFB1	100 % reduction in 24 h in 15 kGy	Gillani et al. (2022)
	Aflatoxins	100 % reduction in 24 h in 15 kGy	
	OTA	100 % reduction in 24 h in 15 kGy	
	ZEA	97 % reduction in wheat in 20 kGy	Sebaei et al. (2022)
		51 % reduction in yellow corn in 20 kGy	
		59.9 % reduction in white corn in 20 kGy	
	AFB1	86.9 % reduction with 17.28 J	Bulut et al. (2020)
	AFB2	98.7 % reduction with 17.28 J	
	AFG1	94.7 % reduction with 17.28 J	
	AFG2	92.7 % reduction with 4.08 J	
	AFB1	97.75 % reduction with 17.28 J	Evrendilek et al. (2022)
	AFB2	99.58 % reduction with 17.28 J	
Ultrasound Bath	AFG1	99.88 % reduction with 17.28 J	
	AFG2	99.47 % reduction with 17.28 J	
	OTA	37 % reduction in 10 min	Ertek et al. (2024)
High Voltage Atmospheric Cold Plasma	AFM1	78.9 % reduction with 80 kV 200 W 60 Hz 20 min	Nguyen, Palmer, Phan, et al. (2022)
Cold Plasma	OTA	55.64 % reduction, 8 min at 25 kV	Guo et al. (2023)
	DON	61.25 % reduction, 8 min at 25 kV	
		83.99 % reduction, 8 min at 50 kV	Chen, Qiu, et al. (2022)
Clinoptilolite	Aflatoxins	72 %–89 % binding	Oguz et al. (2022)
Sepiolite		92 %–98 % binding	
Montmorillonite		77 %–80 % binding	
Clinoptilolite, Sepiolite, Bentonite, Montmorillonite		84 %–91 % binding	
Bentonite		87 %–95 % binding	

(continued on next page)

Table 2 (*continued*)

Physical Treatments	Target Mycotoxins	Effects	References
Bentonite, Clinoptilolite, Montmorillonite, Glucomannan, Plant extract *(Rosmarinus officinalis + Cynara scolymus)*		79 %–86 % binding	
Bentonite, Sepiolite, Glucomannan, Plant extract (natural polyphenols + antioxidants)		71 %–72 % binding	
Sodium Bentonite, Thymoquinone, *Nigella sativa*		Amelioration of biomarkers of tissue degeneration in broiler chicken	Dik et al. (2023)
Bentonite		73 % binding	Gillani et al. (2022)
Activated Charcoal		96 % binding	
Clinoptilolite	OTA	51 %–62 % binding	Oguz et al. (2022)
Sepiolite		54 %–53 % binding	
Montmorillonite		54 % binding	
Clinoptilolite, Sepiolite, Bentonite, Montmorillonite		53 %–56 % binding	
Bentonite		53 %–56 % binding	
Bentonite, Clinoptilolite, Montmorillonite, Glucomannan, Plant extract (*Rosmarinus officinalis + Cynara scolymus)*		51 %–74 % binding	
Bentonite, Sepiolite, Glucomannan, Plant extract (natural polyphenols + antioxidants)		51 %–53 % binding	
Bentonite		93 % binding	Gillani et al. (2022)
Activated Charcoal		43 % binding	
Calcium montmorillonite		25.1 % binding	Appell et al. (2023)
Sodium montmorillonite		23 % binding	
Sodium bentonite		17.1 % binding	
Activated Coconut Charcoal		95.9 % binding	
Pine Biochar		97.3 % binding	
Horticulture Biochar		25.6 % binding	
Olive Wood Biochar		81.2 % binding	
β-cyclodextrin bead polymer		82 % removal in pH 3	Mohos et al. (2022)
Clinoptilolite	ZEA	10 %–27 % binding	Oguz et al. (2022)
Sepiolite		29 %–39 % binding	
Bentonite		27 %–30 % binding	
Bentonite, Clinoptilolite, Montmorillonite, Glucomannan, Plant extract (*Rosmarinus officinalis + Cynara scolymus)*		29 %–31 % binding	
Bentonite, Sepiolite, Glucomannan, Plant extract (natural polyphenols + antioxidants)		25 %–35 % binding	
Montmorillonite		32 %–53 % binding	
Clinoptilolite, Sepiolite, Bentonite, Montmorillonite		30 %–41 % binding	
Calcium montmorillonite		44.2 % binding	Appell et al. (2023)
Sodium montmorillonite		33.3 % binding	
Sodium bentonite		33.4 % binding	
Activated Coconut Charcoal		88.4 % binding	
Pine Biochar		86.7 % binding	
Horticulture Biochar		21.8 % binding	
Olive Wood Biochar		55.4 % binding	
β-cyclodextrin bead polymer		88 % removal in pH 5	Mohos et al. (2022)
	DON	9 % removal in pH 5	
Clinoptilolite		60 %–68 % binding	Oguz et al. (2022)
Sepiolite		35 %–67 % binding	
Bentonite		22 %–72 % binding	
Bentonite, Clinoptilolite, Montmorillonite, Glucomannan, Plant extract *(Rosmarinus officinalis + Cynara scolymus)*		31 %–52 % binding	
Bentonite, Sepiolite, Glucomannan, Plant extract (natural polyphenols + antioxidants)		24 %–62 % binding	
Montmorillonite		45 %–67 % binding	
Clinoptilolite, Sepiolite, Bentonite, Montmorillonite		31 %–47 % binding	
Pillared Montmorillonite		14.7 %–23.6 % binding in pH 2.0 21.8 %–27.4 % binding in pH 6.8	Zhang et al. (2021)
Clinoptilolite	Fumonisins	9 %–41 % binding	
Sepiolite		39 %–45 % binding	
Bentonite		40 %–32 % binding	
Bentonite, Clinoptilolite, Montmorillonite, Glucomannan, Plant extract *(Rosmarinus officinalis + Cynara scolymus)*		32 %–54 % binding	
Bentonite, Sepiolite, Glucomannan, Plant extract (natural polyphenols + antioxidants)		17 %–36 % binding	
Montmorillonite		34 %–40 % binding	
Clinoptilolite, Sepiolite, Bentonite, Montmorillonite		18 %–42 % binding	
Clinoptilolite	T-2	35 %–37 % binding	
Sepiolite		18 %–38 % binding	
Bentonite		18 %–34 % binding	
Bentonite, Clinoptilolite Montmorillonite, Glucomannan, Plant extract *(Rosmarinus*		28 %–44 % binding	

(*continued on next page*)

Table 2 (*continued*)

Physical Treatments	Target Mycotoxins	Effects	References
officinalis + *Cynara scolymus)*			
Bentonite, Sepiolite, Glucomannan, Plant extract (natural polyphenols + antioxidants)		33 %–36 % binding	
Montmorillonite		11 %–37 % binding	
Clinoptilolite, Sepiolite, Bentonite, Montmorillonite		18 %–27 % binding	
Clinoptilolite	HT-2	24 %–34 % binding	
Sepiolite		11 %–42 % binding	
Bentonite		26 %–34 % binding	
Bentonite, Clinoptilolite Montmorillonite, Glucomannan, Plant extract *(Rosmarinus officinalis* + *Cynara scolymus)*		41 %–42 % binding	
Bentonite, Sepiolite, Glucomannan, Plant extract (natural polyphenols + antioxidants)		10 %–37 % binding	
Montmorillonite		24 %–44 % binding	
Clinoptilolite, Sepiolite, Bentonite, Montmorillonite		19 %–49 % binding	
β-cyclodextrin bead polymer	AFM1	28 % removal in pH 5	Mohos et al. (2022)
	AFB1	56 % removal in pH 5	
Bentonite		92 % binding	Gillani et al. (2022)
Activated Charcoal		96 % binding	
		Amelioration of biochemical parameters, growth parameters and antioxidant capacity in broiler chickens	Alharthi et al. (2022)
Zeolite		Amelioration of biochemical parameters, growth parameters and antioxidant capacity in broiler chickens	
Calcium montmorillonite		28.8 % binding	Appell et al. (2023)
Sodium montmorillonite		25.8 % binding	
Sodium bentonite		20.8 % binding	
Activated Coconut Charcoal		93.2 % binding	
Pine Biochar		93.6 % binding	
Horticulture Biochar		36.6 % binding	
Olive Wood Biochar		73.4 % binding	
Cholestiramine, oxihumate		Amelioration of residue in tissue and histological lesions in broiler chickens	Ali, Fahmy, et al. (2021)
Bifidobacterium bifidum, Polyvinylpyrrolidone		90 % reducing	Aalipanah et al. (2022)
Chitosan, Sodium Dodecyl Sulfate, Activated Carbon		92.4 % adsorption in 40 min	Ji et al. (2025)
	AFB2	91.5 % adsorption in 40 min	
	AFG1	86.4 % adsorption in 40 min	
	AFG2	89.1 % adsorption in 40 min	
Clinoptilolite	AFB1, OTA	Amelioration of biochemical parameters, growth parameters and reducing residue in tissue in broiler chickens	Raj et al. (2021)
Clinoptilolite, *Bacillus subtilis, Bacillus licheniformis, Saccharomyces cerevisiae,* silymarin		Amelioration of biochemical parameters, growth parameters and histological lesions in broiler chickens	Tsiouris et al. (2021)
Nanosilica, Bentonite	AFB1, OTA, T-2, Fumonisins	Amelioration of performance parameters and histological lesions in broiler chicken	Ghazalah et al. (2021)

Thanks to non-toxic, mercury-free xenon lamps, it provides decontamination without leaving residues on food surfaces (Mahendran et al., 2019). In OTA-contaminated grape juice, 95.29 % of OTA was reported to be degraded into phenylalanine and OTα after pulsed light treatment, thereby ameliorating its toxic effects (Wang et al., 2022). Likewise, high-intensity pulsed light eliminated OTA in raisins, leaving no detectable residues (Ertek et al., 2024). In contrast, lower degradation efficiencies were observed in other food matrices: pulsed light treatment resulted in 57 %–73 % degradation of aflatoxins in apple juice, 50 %–67 % reduction of aflatoxins, and only 36 % reduction of OTA in red pepper powders (Qi et al., 2023; Woldemariam et al., 2022). These comparisons clearly indicate that the efficacy of pulsed light is matrix-dependent. While transparent or low-pigment systems such as grape juice and raisins allow efficient light penetration and achieve near-complete detoxification, more complex and pigment-rich matrices such as red pepper powder restrict the effectiveness of the technology, leading to substantially lower degradation rates.

One of the non-thermal methods used to achieve pasteurisation and food disinfection in foods is pulsed electric field application (Evrendilek & Tanasov, 2017). It was reported that *A. parasiticus* decreased by 60 % and aflatoxins by 86–98 % in sesame seeds and *A. parasiticus* decreased by 64.37 % and aflatoxins by 97 %–99 % in red peppers after pulsed electric field application (Bulut et al., 2020; Evrendilek et al., 2022).

Ultrasound causes mechanical, chemical and thermal effects by generating waves through bubbles and acoustic cavitation. It is used against mycotoxin contamination due to its low energy consumption and process temperature, as well as the fact that it does not cause much quality loss (Alizadeh et al., 2021; Moosavi et al., 2021). In a study, it was reported that the amounts of AFB1, DON, ZEA, and OTA were degraded by 96.5 %, 60.8 %, 95.8 %, and 91.6 %, respectively, by ultrasound treatment from maize (Liu et al., 2019). In a recent study, a 37 % reduction in 10 min was observed in OTA-contaminated raisins washed in an ultrasonic bath (Ertek et al., 2024). In a recent study, it was reported that the AFM1 binding capacity of lactic acid bacteria increased by using ultrasound treatment in UHT skim milk (Güner et al., 2025).

Irradiation is typically classified as the physical removal of mycotoxins; however, it also provides energy to compounds, resulting in reactions that alter molecular structures (Neme & Mohammed, 2017). Irradiation is often characterised as ionising (gamma) irradiation or non-ionising irradiation (UV, solar, microwave) (Shanakhat et al., 2018). Irradiation can effectively reduce or eliminate pathogenic microorganisms in food, but it only partially eliminates mycotoxins. This technique can be applied on an industrial scale and has the capacity to energize and alter the molecular structure of food components through a series of reactions (Karlovsky et al., 2016). It has been reported that irradiation reduces ZEA levels in pineapple juice, orange juice and tomato juice contaminated with ZEA. In addition, it has been shown that irradiation levels up to 10 kGy are safe, while higher radiation doses affect the quality of fruit juices (Kalagatur et al., 2018). In addition, more than 95 % reduction of AFB1 (at 6 kGy) was achieved when gamma irradiation was used for rice processing (Ahsan et al., 2013). Despite the proposal of irradiation as a promising approach for mycotoxin detoxification, its efficacy remains under debate. This is due to the potential for physical, chemical, and biological effects following molecular reactions (Shi et al., 2018). Studies using gamma ray irradiation have reported 32 %–59 % reduction in OTA and AFB1 levels in sorghum (Ben Amara et al., 2022), 51 %–97 % reduction in ZEA levels in wheat, yellow maize and white maize (Sebaei et al., 2022), and elimination of OTA and aflatoxins in maize (Gillani et al., 2022). Studies using microwave treatment reported 9 %–33 % reduction in aflatoxins and OTA levels in maize (Gillani et al., 2022), 72.5 % reduction in pistachios (Jalili et al., 2020) and 40 %–75 % reduction in rice (Chandravarnan et al., 2025).

UV is classified according to its wavelength, and the most harmful light with a wavelength of 315–400 nm is UV-A. This is followed by UV-B with a medium wavelength of 280–315 nm. The UV light with a short wavelength is UV-C with 200–280 nm. The degradation process in mycotoxins is thought to cause DNA damage through photocatalytic reactions (Akhila et al., 2021; Nguyen, Palmer, Loo, et al., 2022). The amounts of AFB1 and AFM1 decreased by 78.2 % and 65.7 %, respectively, following UV-A treatment in milk samples. In addition, in cytotoxicity studies, it was reported that the toxicity caused by aflatoxin decreased with UV-A treatment (Kurup et al., 2022). Studies using UV-C light have reported a 31 %–59 % reduction in aflatoxins and OTA levels in rice (Chandravarnan et al., 2025), a 50 % reduction in AFM1 levels in milk (Nguyen, Palmer, Loo, et al., 2022) and the elimination of aflatoxins and OTA levels in maize (Gillani et al., 2022). It has been reported that UV light may affect the sensory properties of food after prolonged exposure to food and may cause the formation of carcinogenic components by causing lipid peroxidation (Fan et al., 2021; Soro et al., 2023).

Cold plasma has strong antimicrobial effects. Due to its antimicrobial effect, it is used to eliminate pathogens in food processing (Karlovsky et al., 2016; Shanakhat et al., 2018). Plasma, a high-energy ionized gas consisting of UV photons, ions, electrons and free radicals (such as reactive oxygen and nitrogen species), is formed when sufficient energy is supplied to a gas through heat or an electric field, causing free electrons to accelerate to high energies. Collisions between electrons and neutral gas atoms or molecules can lead to ionisation; if a significant number of ionisation events occur, the process becomes self-sustaining and leads to the formation of plasma (Neuenfeldt et al., 2023; Wielogorska et al., 2019). Cold atmospheric pressure plasma technology offers a promising, low-cost, environmentally friendly, fast technique for the decontamination of mycotoxins that preserves product quality compared to methods such as UV and gamma irradiation (Misra et al., 2019; Wielogorska et al., 2019). A colour change was observed in whole milk following the application of cold atmospheric plasma. This colour change is thought to be caused by the oxidation of fat and protein resulting from the cold atmospheric plasma (Nikmaram & Keener, 2022; Oliveira et al., 2025). Cold plasma targets fungal spores and the DNA responsible for mycotoxin biosynthesis, causing disruptions in protein and lipid synthesis (Zhao et al., 2024). It also converts mycotoxins into less toxic metabolites. Although there is limited information about the degradation products of mycotoxins through this pathway, two mycotoxins are well understood. It reduces the toxicity of AFB1 by breaking the C_8-C_9 bond responsible for toxicity in the furan ring (Hojnik et al., 2021; Wang et al., 2024). DON, on the other hand, reduces its toxicity by breaking down the hydroxyl group at C3, the C_9-C_{10} and C_{12}-C_{13} double bonds (Chen, Qiu, et al., 2022). Studies using cold plasma treatment reported 66 % reduction in AFB1 and FB1 levels in maize (Wielogorska et al., 2019), 78.9 % reduction in AFM1 levels in milk (Nguyen, Palmer, Phan, et al., 2022), Nguyen, Palmer, Phan, et al., 2022nd 55 %–61 % reduction in DON and OTA levels in rice (Guo et al., 2023). In another study, DON was transformed into less toxic metabolites by undergoing 83.99 % degradation (Chen, Qiu, et al., 2022).

2.1.3. *Mycotoxin binders*

Mycotoxin binders are also referred to as adsorbents, separators, inhibitor molecules, sequestering agents, sequestrants, or enterosorbents (Jard et al., 2011). These binders usually have a high molecular weight and, in animals consuming feed contaminated with mycotoxins, the contaminated feed binds to the mycotoxin binders before being absorbed into the animal's gastrointestinal tract. The binding agent and the mycotoxin form a complex that is excreted in the faeces. As a result, mycotoxin exposure is prevented or minimized (Boudergue et al., 2009).

2.1.3.1. Silicate binders. Silicate binders contain structural units composed of silicon atoms tetrahedrally coordinated by oxygen atoms (Kihal et al., 2022). In these arrangements, each silicon atom forms covalent bonds with four oxygen atoms, generating SiO_4 tetrahedra. These tetrahedra can link through shared oxygen atoms, resulting in diverse structural types such as chains, sheets, rings, and three-dimensional frameworks. The organization of these tetrahedral layers plays a crucial role in the adsorption capacity of silicate binders. Silicates are broadly classified into phyllosilicates (e.g., bentonite, montmorillonite, smectite, kaolin, illite, HSCAS) and tectosilicates (e.g., zeolites, clinoptilolites), based on the way these tetrahedra are connected (Di Gregorio et al., 2014; Kabak et al., 2006). The adsorption capacity of silicate materials can be influenced by thermal processing. For instance, heating clinoptilolite at 300 °C, 450 °C, and 600 °C was shown to enhance its mycotoxin, moisture, and gas binding capacity up to four times (Eseceli et al., 2017).

Recent studies have demonstrated the effectiveness of various mycotoxin binders against different toxins. Calcium and sodium montmorillonite were reported to bind AFB1, OTA, and ZEA by 17.1 %–44.2 % by stimulating the gastric environment (Appell et al., 2023), while bentonite bound aflatoxin and OTA in maize by 73 %–93 % (Gillani et al., 2022). Pillared montmorillonite was observed to bind 14.7 %–23.6 % of DON at pH 2.0 and 21.8 %–27.4 % at pH 6.8, and its effectiveness could be enhanced by using pillaring reagents compared to raw montmorillonite (Zhang et al., 2021).

In vitro studies investigating multiple mycotoxins showed that glucomannan, clinoptilolite, sepiolite, bentonite, montmorillonite, and several commercial products exhibited high binding capacity, particularly for DON and OTA. Moreover, the addition of glucomannan and plant extracts further increased binding levels (Oguz et al., 2022).

Studies focusing on the protective effects of adsorbents against mycotoxin toxicity revealed that clinoptilolite reduced OTA and AFB1 residue levels (Raj et al., 2021). A combination of nanosilica and bentonite was effective against AFB1, OTA, T-2, and fumonisin toxicity (Ghazalah et al., 2021). Zeolite and bentonite showed curative effects against AFB1 (Alharthi et al., 2022), while thymoquinone, the main component of *Nigella sativa*, together with sodium bentonite, was effective against aflatoxin toxicity (Dik et al., 2023). Additionally, a mycotoxin detoxifying agent containing clinoptilolite, *Bacillus subtilis, Bacillus licheniformis, Saccharomyces cerevisiae* cell walls, and silymarin

demonstrated ameliorative effects against OTA and AFB1 toxicity (Tsiouris et al., 2021).

2.1.3.2. Carbon binders. Insoluble powders formed as a result of heating organic compounds such as wood and coal at temperatures up to 2000 °C are called activated carbon (Galvano et al., 1996; Pulido-Novicio et al., 2001). It is activated by increasing its adsorption ability as a result of physical and chemical processes. Chemical processes pose a danger by producing significant residues in terms of environmental toxicity (Danish & Ahmad, 2018). The disadvantage of using activated carbon as a mycotoxin binder is that it does not bind specifically. It may cause negative effects on the nutrient content of the feed by reducing the adsorption of vitamins, minerals and nutrients (Avantaggiato et al., 2005; Ramos et al., 1996). Although silicate binders demonstrate higher aflatoxin binding, activated carbon exhibits greater binding to ZEA and DON (Avantaggiato et al., 2004). The higher binding properties of activated carbon compared to silicate binders are explained by the fact that the interlayer space of the pore of activated carbon is larger and less selective than the interlayer space of silicate binders (De Mil et al., 2015; Nuryono et al., 2012).

Studies investigating the binding of mycotoxins by carbon-based adsorbents reported that four different coal-based compounds bound AFB1, OTA, and ZEA by 36.6 %–93.6 %, 25.6 %–97.3 %, and 21.8 %–88.4 %, respectively (Appell et al., 2023). In maize, these compounds achieved 43 %–96 % binding of OTA and aflatoxins (Gillani et al., 2022), while the combination of coal-based adsorbents with sodium dodecyl sulfate and chitosan resulted in 89.9 % binding of aflatoxins (Ji et al., 2025).

2.1.3.3. Synthetic polymers binders. Polymers such as cholestyramine, styrene, polyvinylpyrrolidone, and divinylbenzene can bind mycotoxins (Aalipanah et al., 2022; Avantaggiato et al., 2005). Cholestyramine is a resin that binds bile acids and binds against OTA, fumonisin and ZEA (Avantaggiato et al., 2005; Solfrizzo et al., 2001). In studies investigating the effect of polymers against mycotoxins, the addition of 2 % cholestyramine reduced the sphinganin/sphingosine ratios caused by fumonisin (Solfrizzo et al., 2001). Polyvinylpyrrolidone combined with *Bifidobacterium bifidum* strain had a synergistic effect against AFB1, and the reduction effect increased from 50 % to 90 % (Aalipanah et al., 2022). In another study, it was reported that AFB1, AFM1, DON, OTA, and ZEA mycotoxins were removed by 56 %, 28 %, 9 %, 82 % and 88 %, respectively, using β-cyclodextrin bead polymer. The highest removal of OTA was observed at pH 3, and other mycotoxins at pH 5 (Mohos et al., 2022). It was also reported that the combination of cholestyramine and oxyhumate was effective against AFB1 toxicity in chickens (Ali, Fahmy, et al., 2021).

2.1.3.4. Dietary fiber binders. Small structures obtained from cereals and vegetable products, such as wheat, barley, oats, cellulose, lignin, and hemicellulose, are collectively referred to as micro-ionized fibers. According to Aoudia et al. (2008), these fibers can protect against OTA contamination by binding mycotoxins in the digestive tract, reducing their intestinal absorption, and increasing their excretion in faeces. Previous studies reported that grape pomace adsorbed AFB1, OTA, ZEA, and FB1 (Avantaggiato et al., 2014), while grape pomace, artichoke waste, and almond shells exhibited high binding activity against AFB1, ZEA, and OTA (Greco et al., 2019). In a recent study, the binding capacity of different dietary fibers against various mycotoxins was investigated through *in vitro* digestion of fiber-enriched biscuits. κ-carrageenan was effective in reducing ZEA bioaccessibility, and the incorporation of apple pomace flour (sugar-free) further mitigated the effects of DON, HT-2, and T-2. These results suggest that the inclusion of dietary fibers in biscuit formulations may decrease the bioaccessibility of mycotoxins and enhance food safety (López-Ruiz et al., 2023).

2.2. Chemical control methods

In the decontamination of mycotoxins, chemical treatments have been widely applied because they can significantly reduce toxin levels in foods and feeds, although their use may sometimes lead to undesirable effects on nutritional quality and sensory properties (Awad et al., 2010; Kabak et al., 2006; Nazhand et al., 2020). The main agents used for these treatments include alkalis (e.g., ammonia gas, sodium hydroxide, calcium hydroxide), acids (e.g., acetic, phosphoric, formic, propionic, and sorbic acids, as well as sodium hypochlorite), reducing agents (e.g., sodium bisulphite), and oxidising reagents (e.g., ozone, hydrogen peroxide). Recent studies on the reduction of mycotoxins using such chemical control methods are summarized in Table 3.

AFB1 is converted to Aflatoxin D, a less toxic metabolite, through ammonification, thereby reducing its toxic effect. (The reactions that occur are hydrolysis in the lactone ring, decarboxylation to Aflatoxin D, and loss of the cyclopentane ring, respectively). In addition, increasing ammonia levels in feed and feed raw materials may cause a decrease in nutritional values (Hojnik et al., 2017; Jouany, 2007; Negash, 2018). It

Table 3
Mycotoxins removal percentage of chemical agents.

Chemical Treatments	Target Mycotoxins	Effects	References
Paracetic acid	OTA	52.35 % reduction in 10 min	Ertek et al. (2024)
Potassium hydroxide		65.25 % reduction in 10 min	
Alkaline hydrogen peroxide		63.30 % reduction in 5 min	
Potassium carbonate		66.60 % reduction in 5 min	
Ozone, UV-C		84.07 % degradation at 15 cm in 180 min 80.94 % degradation at 15 cm in 180 min	Alnaemi et al. (2025)
Ammonia gas	AFB1	Amelioration of biochemical parameters, growth parameters and antioxidant capacity in sheep	Zhang, Jiao, et al. (2022)
Ozone	Aflatoxins, ZEA, DON	Mycotoxin eliminated in 180 min in maize hybrids (40, 70, 85 mg/l)	Purar et al. (2022)
	AFB1	98 % in 30 min in peanut milk	Romero et al. (2023)
	AFB2	32 % in 180 min in peanut milk	
	AFG1	99 % 30 min in peanut milk	
	AFG2	41 % in 210 min in peanut milk	
	AFB1	97 % reduction in high concentration short-time treatment 86 % reduction in low concentration long-time treatment	Ozel and Karaca (2024)
	DON	Amelioration of biochemical parameters, growth parameters, histological lesions and immunological parameters in mouse	Sun et al. (2023)
	Aflatoxins	90 % reduction in peanuts 81.8 % reduction in pistachios 84.4 % reduction in almonds	Ali and Abdallah (2022)
Ozone, citric acid, UV-C		>90 % degradation in 30 min, 3 N, 36 h	Babaee et al. (2022)
UV-C, Ozone	FB1	83.6 % degradation at 15 cm in 180 min	Alnaemi et al. (2025)
Ozone		81.2 % reduction in 13.5 mg/L in 24 h	Ribeiro et al. (2022)
	FB2	81.6 % reduction in 13.5 mg/L in 24 h	

was reported that the toxic effects of AFB1 in sheep were reduced by ammonia gas treatment (Zhang, Jiao, et al., 2022).

There is also the use of acid as a chemical agent in the detoxification of mycotoxins. AFB1 is biotransformed at acid pH to Aflatoxin B2a, a detox product with less toxic effects (Rushing & Selim, 2019). Sodium bisulphite detoxifies aflatoxins and trichothecenes by reducing the epoxide rings in the reduction reaction with these mycotoxins (Karlovsky et al., 2016). After heating 30 ml of lemon juice and 6 g citric acid mixture at 120 °C for 1 h, a 93.4 % reduction in AFB1 was recorded in pistachios. However, deterioration in the organoleptic properties of pistachios was observed. Using a mixture of 15 ml lemon juice, 2.25 g citric acid, 49.2 % AFB1 reduction was recorded, and no change was observed in pistachios (Rastegar et al., 2017). In a study conducted to reduce OTA contamination in raisins, a 52.35 % reduction was observed after 10 min of treatment with peracetic acid, a 62.25 % reduction after 10 min of treatment with potassium hydroxide, a 66.6 % reduction after 5 min of treatment with potassium carbonate, and a 63.3 % reduction after 5 min of treatment with alkaline hydrogen peroxide (Ertek et al., 2024).

Ozone technology, which has antiseptic properties as a strong oxidant, is used in gas and liquid form to control the growth of fungi and decontamination of mycotoxins thanks to its oxidising reaction. Ozone has been widely used for post-harvest mycotoxin management due to its absence of residue (Horvitz & Cantalejo, 2014). Ozone interacts with the C_8-C_9 epoxide furan ring responsible for the toxicity of aflatoxins through electrophilic attack, thereby reducing the toxicity of aflatoxins. Similarly, ozone interacts with the C_9-C_{10} double bond responsible for DON toxicity through electrophilic attack and contributes to the reduction of DON toxicity by oxidising the C_8 allylic carbon. Additionally, ozone reacts with the chlorinated aromatic ring of OTA, causing the release of free chlorine and the formation of amino acid derivatives, thereby reducing its toxicity (Afsah-Hejri et al., 2020; He et al., 2010; Tiwari et al., 2010). It has been reported that aflatoxins, ZEA and DON were eliminated in maize after ozone treatment, and the amount of linoleic acid in maize decreased (Purar et al., 2022). In studies conducted with ozone application, it has been reported that aflatoxins in peanut milk decreased by 32 %–99 % and changes in sensory properties by causing the breakdown of fatty acids in products (Romero et al., 2023), aflatoxins in peanuts, pistachios and almonds decreased by 81 %–90 % (Ali & Abdallah, 2022), FB1 and FB2 levels in corn decreased by 81 %–86 % (Ribeiro et al., 2022). In a recent study, it was reported that high-concentration short-term and low-concentration long-term ozone treatment caused 1.57 log and 1.66 log reduction in the amount of *A. flavus* and 97 % and 86 % reduction in the amount of AFB1, respectively (Ozel & Karaca, 2024). It was reported that the toxic effects of DON in mice were reduced by ozone treatment (Sun et al., 2023).

In a study using ozone gas, UV-C and citric acid, it was reported that aflatoxins were reduced by 90–99 % and citric acid increased the effectiveness of ozone (Babaee et al., 2022). In the study conducted with the combination of UV-C and ozone application, 80–83 % degradation of AFB1, OTA and FB1 was recorded. A decrease in the moisture level and protein content of the feed was recorded (Alnaemi et al., 2025).

2.3. Biological control methods

In recent years, there have been biological measures of increasing importance for mycotoxin decontamination in feed, feed raw materials and foods. Biological decontamination methods are less costly, more limited nutrient loss, less or no toxic by-products, have more specific targets, more environmentally friendly compared to other control methods (Sarrocco & Vannacci, 2018; Yang et al., 2023). In this control method, microorganisms such as bacteria, yeasts and enzymes biologically transform mycotoxins, ensure their enzymatic degradation or transform them into less toxic metabolites (Hathout & Aly, 2014). Due to enzymatic degradation, fermentation is an effective processing method to reduce the number of mycotoxins (Lancova et al., 2008).

2.3.1. Bacteria

One of the microorganisms for the biological reduction of mycotoxins is bacteria. The most widely known of these are lactic acid bacteria. These bacteria act as organic binders in the detoxification process either by binding to the cell wall of mycotoxins or by secreting compounds or producing enzymes that negatively affect fungal growth and development (Dalié et al., 2010). Recent studies on the reduction of mycotoxins by using bacteria from biological control methods are summarized in Table 4.

It was reported that OTA levels in coffee beans decreased by 77.33 % after inoculation with *Bacillus licheniformis* M2-7 (Rojas-Pablo et al., 2024). For AFB1 detoxification, *Bacillus subtilis* B-59994, *Bacillus subtilis* SCK6, *Bacillus* sp. H16v8 *and Bacillus* sp. HGD9229, *Bacillus amyloliquefaciens* ZG08, *Bacillus albus* YUN5, *Bacillus aryabhattai, Bacillus amyloliquefaciens* YUAD7 were reported to be 60 %, 76.93 %, 56.7 %, 80.93 %, 54.96 %, 82.92 %, 91.7 % effective, respectively (Kumar et al., 2023; Qin et al., 2021; Shi, Chang, et al., 2024; Suresh et al., 2020; Tang et al., 2023, 2024; Wang et al., 2021). Additionally, it has been reported that *Bacillus amyloliquefaciens HNGD*-DF2 degraded AFB1 and ZEA by 99.9 % and 87.4 % respectively, while reducing them by 87.53 % and 71.6 % in wheat flour and by 95 % and 80.04 % in corn flour, respectively (Muzaffar et al., 2025). *Bacillus subtilis* SCK6 strain was reported to reduce DON and ZEA levels by 78 %–84 % (Qin et al., 2021), *Bacillus* sp. HN117 and *Bacillus* sp. N22 strains metabolized DON by 21 %–29 % (Li et al., 2022), *Bacillus velezensis* IS-6 strain metabolized 89 % of OTA (Jahan et al., 2023), *Bacillus velezensis* E2 strain achieved a 96.1 % reduction in OTA (Zhang, Li, et al., 2022), *Bacillus albus* YUN5 strain reduced aflatoxins by 46 %–97 % (Kumar et al., 2023), and *Bacillus spizizenii* B73 strain degraded 99.3 % of ZEA, with degradation efficiencies ranging from 80 % to 98 % in wheat bran, DDGS, and corn flour (Liu et al., 2023). *Bacillus amyloliquefaciens* D-1, *Bacillus subtilis* YQ-1, *Bacillus* sp. S62-W, *Bacillus subtilis* Y816 strains were reported to degrade ZEA to 96.13 %, 98.36 %, 100 %, and 100 % transformation products, respectively (Deng et al., 2023; Yang et al., 2021; Zhou et al., 2024; Zhu, Drouin, et al., 2021). Overall, *Bacillus* strains exhibit high detoxification potential across multiple mycotoxins, with particularly strong efficacy against ZEA (often exceeding 95 %–100 % degradation), moderate-to-high efficiency against OTA (77 %–96 %), and more variable results for DON (21 %–84 %) and AFB1 (55 %–92 %). This highlights their versatility, although strain-specific differences in effectiveness are evident.

In a study, it was reported that *Brevibacterium* spp. strains detoxified all of OTA to OTα, *Rhodococcus erythropolis* strains detoxified 19 %–28 % and *Pseudomonas putida* strains detoxified 8 %–25 % (Rodriguez et al., 2011). Ruminants utilise microbial fermentation to digest food because they have a rumen containing microorganisms. This allows them to detoxify certain toxins through microbial detoxification, which is not possible for monogastric species. These microorganisms break down the 12,13-epoxy rings of DON and trichothecenes, converting them into less toxic metabolites and conferring resistance to these toxins in ruminants. The strain *Eubacterium* spp. BBSH 797 was isolated from rumen microbiota, and a commercial product based on this strain has been developed (Binder, 2007; Schatzmayr et al., 2006). *Devosia mutans* 17-2-E−8 bacterial strain was reported to reduce the toxicity of DON by biological conversion of DON to its less toxic metabolites, 3-epi-DON main product and 3-keto-DON (He et al., 2015). It was reported that *Citrobacter freundii* ON077584 strain degraded over 90 % of DON into 3-keto-DON and deepoxy-deoxynivalenol (Murtaza et al., 2023), while *Pelagibacterium halotolerans* ANSP101 converted 80 % of DON into the less toxic 3-keto-DON (Zhang et al., 2020). It was reported that *Lactobacillus acidophilus* CIP 76.13 T and *Lactobacillus delbrueckii* subsp. *bulgaricus* CIP 101027 T strains degraded ZEA by 57 %–28 % and DON by 30 %, respectively (Ragoubi et al., 2021). *Cupriavidus* species exhibited notable biodegradation activity against mycotoxins, with degradation rates ranging from 72 % to 97 % for AFB1, ZEA, and OTA (Al-Nussairawi et al., 2020).

Table 4
Mycotoxins removal percentage of different bacterial strains.

Bacteria	Target Mycotoxins	Effects	References
Bacillus subtilis B-59994	AFB1	60 % degradation in 100 h	Suresh et al. (2020)
Bacillus subtilis SCK6		76.93 % degradation in 48 h	Qin et al. (2021)
Bacillus sp. H16v8 and *Bacillus* sp. HGD9229		56.7 % degradation in 12 h	Wang et al. (2021)
Bacillus megaterium HNGD-A6		94.66 % degradation in 72 h	Cheng et al. (2023)
Bacillus amyloliquefaciens ZG08		80.93 % degradation in 72 h	Shi, Chang, et al. (2024)
Bacillus amyloliquefaciens HNGD-D		99.9 % degradation at 80 °C 87.53 % degradation in wheat flour 95 % degradation in maize flour	Muzaffar et al. (2025)
Bacillus albus YUN5		54.96 % degradation in 120 h	Kumar et al. (2023)
Bacillus aryabhattai		82.92 % degradation in 72 h	Tang et al. (2023)
Lactobacillus salivarius		Amelioration of performance parameters, liver function, meat quality, immune support and *Salmonella pullorum* infection resistance in broiler chicken	Chen, Ishfaq, and Wang (2022)
Lactobacillus spp.		60 % reduction	Chlebicz and Slizewska, 2020
Lactobacillus salivarius		Amelioration of biochemical parameters, reduction in oxidative stress parameters and inhibition of mitochondrial mitophagy in geese	Qiu et al. (2024)
Pediococcus pentosaceus L6		46.4 % reduction	Asurmendi et al. (2020)
Lactiplantibacillus plantarum L12		49.7 % reduction	
Leuconostoc mesenteroides L18		37.6 % reduction	
Leuconostoc mesenteroides L19		50 % reduction	
Lactobacillus coryniformis L47		49.1 % reduction	
Levilactobacillus brevis L52		70.7 % reduction	
Bacillus amyloliquefaciens YUAD7		91.7 % degradation in 72 h	Tang et al. (2024)
Lactobacillus casei shirota		48–62 % removel with heat-treated cells	Ondiek et al. (2022)
Lactobacillus plantarum FJS003		89.5 % reduction	Zhu, Xu, and Yang (2021)
Lactobacillus plantarum T3		Increase excretion of toxins in faeces, improvement in biochemical parameters and oxidative stress in ICR mice	Tian et al. (2022)
Bacillus subtilis, Lactobacillus casein, Enterococcus faecalis, Candida utilis, Montmorillonite		Amelioration of performance parameters and reducing residual mycotoxin in broiler chicken	Guo et al. (2021)
Cupriavidus laharis CCUG 53908		91 % degradation	Al-Nussairawi et al. (2020)
Cupriavidus numazuensis DSM 15562		72 % degradation	
Bacillus albus YUN5	AFB2	46.22 % degradation in 120 h	Kumar et al. (2023)
	AFG1	97.47 % degradation in 120 h	
Bacillus albus YUN5	AFG2	95.97 % degradation in 120 h	Kumar et al. (2023)
Lactobacillus rhamnosus GG	AFM1	64.6 % reduction	Nahle et al. (2022)
Lactococcus lactis ssp. *cremoris*		81.4 % reduction	Muaz et al. (2021)
Lactococcus lactis ssp. *lactis*		50.8 % reduction	
Lacticaseibacillus rhamnosus		56.8 % reduction	
Lacticaseibacillus rhamnosus, Lactococcus lactis		94 % reduction in 30 d	Gonçalves et al. (2020)
Lactobacillus fermentum 111, *Lacticaseibacillus paracasei* 108, *Lactiplantibacillus plantarum* 49		80 % reduction in 24 h	Cruz et al. (2020)
Bacillus velezensis IS-6	OTA	89 % degradation in 24 h	Jahan et al. (2023)
Bacillus velezensis E2		96.1 % degradation in 48 h	Zhang, Li, et al. (2022)
Bacillus licheniformis M2-7		77.33 % reduction	Rojas-Pablo et al. (2024)
Lactobacillus rhamnosus GG		98.3 % reduction	Nahle et al. (2022)
Bacillus subtilis fermentation extract		Decreasing toxic effect in broiler chicken	Elhady et al. (2022)
Cupriavidus alkaliphilus BCCM 26294		95 % degradation	Al-Nussairawi et al. (2020)
Cupriavidus taiwanensis CCUG 44338		97 % degradation	
Cupriavidus basilensis DSM 11853		94 % degradation	
Cupriavidus numazuensis DSM 15562		85 % degradation	
Cupriavidus pinatubonensis DSM 19553		88 % degradation	
Cupriavidus basilensis DSM 11853	ZEA	96 % degradation	
Cupriavidus numazuensis DSM 15562		85 % degradation	
Cupriavidus pinatubonensis DSM 19553		91 % degradation	
Bacillus spizizenii B73		99.3 % degradation in 8 h	Liu et al. (2023)
Bacillus amyloliquefaciens D-1		96.13 % degradation in 24 h	Deng et al. (2023)

(*continued on next page*)

Table 4 (*continued*)

Bacteria	Target Mycotoxins	Effects	References
Bacillus amyloliquefaciens HNGD-D		87.4 % degradation at 70 °C 71.6 % degradation in wheat flour 80.04 % degradation in maize flour	Muzaffar et al. (2025)
Bacillus subtilis YQ-1		98.36 % degradation in 16 h	Zhou et al. (2024)
Bacillus sp. S62-W		100 % degradation in 24 h	Zhu, Drouin, et al. (2021)
Bacillus subtilis Y816		100 % degradation in 12 h	Yang et al. (2021)
Bacillus subtilis SCK6		84.65 % degradation in 48 h	Qin et al. (2021)
Lactobacillus delbrueckii subsp. *bulgaricus* CIP: 101027 T, *Lactobacillus acidophilus* CIP 76.13 T		57 % degradation in PBS- 28 % degradation in MRS	Ragoubi et al. (2021)
Lactobacillus spp.		57 % reduction	Chlebicz and Slizewska, 2020
Lactobacillus plantarum MON03		Amelioration of oxidative stress parameters and improvement of adverse changes in biochemical parameters in BALB/c mice	Salah-Abbes et al. (2021)
		Amelioration of reprotoxicity in male mice	Belgacem et al. (2022)
Lactobacillus paracasei		83.93 % biosorption	Złoch et al. (2020)
Kefir		Amelioration of oxidative stress, histological lesions and antioxidant enzymes in Wistar rats	Taheur et al. (2022)
Citrobacter freundii ON077584	DON	90 % degradation to metabolites	Murtaza et al. (2023)
Lactobacillus spp.		19–39 % reduction	Chlebicz and Slizewska, 2020
Bacillus sp. HN117 *and Bacillus* sp. N22		29 % in 72 h, 21.21 % degradation in 120 h	Li et al. (2022)
Lactiplantibacillus plantarum AR524		50.53 % reduction	Cao et al. (2021)
Bacillus subtilis SCK6		78.42 % degradation in 48 h	Qin et al. (2021)
Pelagibacterium halotolerans ANSP101		80 % degradation in 12 h	Zhang et al. (2020)
Enterecoccus casseliflavus M4A	FB1	88.75 % reduction	Diaz et al. (2021)
Lactobacillus paracasei BEJ01		Amelioration of liver damage, kidney damage, oxidative stress, histological damage in BALB/c mice	Ezdini et al. (2020)
Lactobacillus spp.	FB1, FB2	62 %–77 % reduction	Chlebicz and Slizewska, 2020
	T-2	61 % reduction	
Lactobacillus casei shirota		42 %–53 % removel with heat-treated cells	Ondiek et al. (2022)
Lactiplantibacillus plantarum LUHS135,	AFB1, OTA, ZEA, T-2, HT-2	Decrease in *in vitro* mycotoxin concentrations and improvement in	Zavistanaviciute et al. (2023)

Table 4 (*continued*)

Bacteria	Target Mycotoxins	Effects	References
Lactocaseibacillus paracasei LUHS244		health parameters of calves	
Pediococcus acidilactici ARKA-CH-7	Aflatoxins	71.74 % reduction	Jam et al. (2024)
Lacticaseibacillus rhamnosus ARKA-CH-9		92.56 % reduction	
LeviLactobacillus brevis ARKA-CH-2		95.67 % reduction	
Lacticaseibacillus rhamnosus ARKA-CH-9, *Levilactobacillus brevis ARKA-CH-2*		Amelioration of biochemical parameters, oxidative stress and histological lesions in BALB/c mice	
Lactobacillus plantarum 299 V, HSCAS		Amelioration of biochemical parameters, histological lesions and performance parameters in broiler chicken	Allameh et al. (2021)
Pumpkin and fermented whey	AFB1, OTA	Increase faecal excretion in Wistar rats	Vila-Donat et al. (2025)

The binding of mycotoxin by LAB naturally present in the intestinal flora reduces the adsorption of the toxin in the gastrointestinal tract, leading to excretion as a bacterial-mycotoxin complex and metabolic detoxification (Dalié et al., 2010; Peltonen et al., 2000). The removal of mycotoxins by LAB strains through adsorption is primarily mediated by the components of their cell walls, which is the most common mechanism for mycotoxin detoxification (Sadiq et al., 2019).

The binding ability of mycotoxins by LAB strains varies depending on the type of growth medium, bacterial viability, type of bacterial strain, mycotoxin concentration in the medium, number of bacteria, temperature and pH. The viability of LAB cells has been the subject of many important studies in terms of mycotoxin adsorption, and as a result, it has been reported that the loss of viability of the bacteria by heat or acid increases the amount of mycotoxin adsorption (El-Nezami et al., 1998; Haskard et al., 2001). Heat and acid treatments increase mycotoxin binding to cell wall components by affecting the integrity of polysaccharides and peptidoglycan structures of the bacterial cell wall. Teichoic acid and polysaccharides in the cell wall are affected by acid treatment, making the bacterial cell wall more bindable by mycotoxin (Haskard et al., 2001).

The hydrophobic and electrostatic interactions involved in the binding of mycotoxin to the bacterial cell wall may change the mycotoxin binding capacity by being affected by pH. In a study, it was observed that the highest binding capacity of AFB1 to *Lactobacillus plantarum* and *Lactobacillus buchneri* was at pH 2.5, and the lowest binding capacity was at pH 8.5 (Ma et al., 2017). This pH range (2.5–8.5) is particularly relevant as it mimics the conditions encountered during gastric digestion and intestinal transit, as well as possible variations occurring in certain food processing environments. DON degradation is more common in acidic pH (Guo et al., 2023).

It was reported that *Lactobacillus plantarum* FJS003 inhibited AFB1 by 89.5 % (Zhu et al., 2022b), while *Lactobacillus* spp. strains adsorbed AFB1, ZEA, DON, FB1–FB2, and T-2 mycotoxins at rates ranging from 19 % to 77 % (Chlebicz & Śliżewska, 2020). *Enterococcus casseliflavus* M4A reduced FB1 biosynthesis by 88.75 % (Diaz et al., 2021), and *Pediococcus acidilactici*, *Lacticaseibacillus rhamnosus*, and *Levilactobacillus brevis* strains reduced aflatoxins by 71 %–95 % (Jam et al., 2024). In addition, *Lactobacillus fermentum* 111, *Lacticaseibacillus paracasei* 108, and *Lactiplantibacillus plantarum* 49 decreased AFM1 by 80 % (Cruz et al., 2020), while *Lactobacillus plantarum* AR524 reduced DON by 50 %

(Cao et al., 2021), and *Lactobacillus paracasei* inactivated ZEA by 83.93 % (Złoch et al., 2020). Furthermore, *Pediococcus pentosaceus* L6, *Lactiplantibacillus plantarum* L12, *Leuconostoc mesenteroides* L18 and L19, *Lactobacillus coryniformis* L47, and *Levilactobacillus brevis* L52 strains inactivated AFB1 by 37 %–50 % (Asurmendi et al., 2020). The AFM1 binding capacities of *Lactococcus lactis* ssp. *cremoris*, *Lacticaseibacillus rhamnosus*, and *Lactococcus lactis* ssp. *lactis* were reported as 50 %–81 % (Muaz et al., 2021), and the detoxification capacities of *Lactobacillus rhamnosus* GG against AFM1 and OTA were reported as 64.6 % and 98.3 %, respectively (Nahle et al., 2022). In another study, the effectiveness of *Lacticaseibacillus rhamnosus* and *Lactococcus lactis* strains in reducing AFM1 was 94 % when used alone, 100 % when used in combination with *Saccharomyces cerevisae* and 100 % when *Saccharomyces cerevisae* was used alone (Gonçalves et al., 2020).

In recent studies conducted in broiler chickens and geese, *Lactobacillus salivarius, Bacillus subtilis, Lactobacillus plantarum* MYS6, *Candida utilis,* and *Lactobacillus casei* strains have reduced the toxic effects caused by ZEA, DON, AFB1, FB1 and OTA (Chang et al., 2020; Chen, Ishfaq, & Wang, 2022; Deepthi et al., 2017; Elhady et al., 2022; Qiu et al., 2024). It was reported that *Lactobacillus plantarum* MON03 reduced ZEA-induced reproductive damage in BALB/c mice (Belgacem et al., 2022; Salah-Abbès et al., 2021). *Bacillus subtilis* ANSB01G, *Devosia* sp. ANSB714, *Lactiplantibacillus plantarum* LUHS135, and *Lacticaseibacillus paracasei* LUHS244 alleviated the toxic effects of ZEA, DON, AFB1, OTA, T-2, and HT-2 in pigs and calves (Shi et al., 2018; Zavistanaviciute et al., 2023). In addition, *Lactobacillus paracasei* BEJ01, *Pediococcus acidilactici*, *Lacticaseibacillus rhamnosus*, and *Levilactobacillus brevis* strains reduced the toxic effects of FB1 and aflatoxins in BALB/c mice (Ezdini et al., 2020; Jam et al., 2024). Furthermore, the probiotic dairy product kefir was found to mitigate the toxic effects of ZEA (Taheur et al., 2022). In a study conducted to reduce AFB1, the 68.5 % *Lactobacillus plantarum* T3 strain showed the highest efficiency among sixty LAB strains. Accordingly, its efficacy in AFB1-induced ICR mice was investigated, and as a result of the research, it was observed that probiotic supplementation increased toxin excretion in faeces and improved the harmful effects of toxin in biochemical blood parameters and oxidative stress parameters (Tian et al., 2022).

An investigation was conducted to evaluate the effects of fermented whey containing probiotics, such as *Lactobacillus* and *Bifidobacterium* strains, together with pumpkin containing beta-carotene, on AFB1 and OTA exposure in rats. The findings indicated that this supplementation increased faecal mycotoxin excretion in both male and female rats, and a higher excretion level was observed in males (Vila-Donat et al., 2025). In another study, *Bacillus subtilis*, *Lactobacillus casei*, *Enterococcus faecalis*, and *Candida utilis* strains, combined with 0.03 % montmorillonite and an aflatoxin-degrading enzyme, achieved 90 % AFB1 detoxification and were reported to reduce AFB1 residues and toxic effects in broiler chickens (Guo et al., 2021). It was reported that a commercial toxin binder containing *Lactobacillus plantarum* 299 V and a commercial mycotoxin binder containing HSCAS reduced aflatoxin-induced liver damage in broiler chickens (Allameh et al., 2021).

2.3.2. Yeast and fungus

Fungi are not only responsible for mycotoxin production but also can degrade the secondary metabolites they produce. *A. niger, A. flavus, Eurotium herbariorum and Rhizopus* spp. fungal strains are involved in the conversion of AFB1 to aflatoxicol, which has about 18-fold lower carcinogenicity (Pawlowski et al., 1977; Wu et al., 2009). Recent studies for the reduction of mycotoxins by using yeast and fungus from biological control methods are summarized in Table 5.

It was reported that *A. niger* RAF106 converted AFB1 into metabolites, 80 % of which were significantly less mutagenic or non-mutagenic (Fang et al., 2020). Additionally, *A. niger* transformed OTA into its less toxic metabolite OTα (Pfohl-Leszkowicz Manderville, 2007), while *Aspergillus tubingensis* M036 and M074 strains converted 95 % of OTA to OTα (Cho et al., 2016). *Trichosporon mycotoxinivorans*, obtained from the

Table 5
Mycotoxins removal percentage of different yeast and fungus strains.

Yeast and Fungus	Target Mycotoxins	Effects	References
Saccharomyces cerevisiae strains	FB1	67 % reduction	Chlebicz and Slizewska, 2020
	FB2	74 % reduction	
	T-2	69 % reduction	
	AFB1	65 % reduction	
	DON	22 %–43 % reduction	
	ZEA	52 % reduction	
Saccharomyces cerevisiae RC016	AFB1	Amelioration of liver damage and histological lesions in broiler chicken	Poloni et al. (2020)
Aspergillus niger RAF106		80 % degradation in 24 h	Fang et al. (2020)
Distillery yeast sludge		Amelioration of performance parameters, oxidative stress, immunsupression and histological lesions in broiler chicken	Khatoon et al. (2024)
Pichia kudriazevii	Aflatoxins	Amelioration of oxidative stress and immunological parameters in broiler chicks	Ali, Khatoon, et al. (2021)
Glucomannan	Aflatoxins	80 %–85 % binding	Oguz et al. (2022)
Glucomannan (Commercial Product)		74 %–84 % binding	
Glucomannan	OTA	54 % binding	
Glucomannan (Commercial Product)		52 %–54 % binding	
β-glucan from Red yeast *Sporidiobolus pararoseus* KM281507		74.10 % reduction	Tapingkae et al. (2022)
Glucomannan	ZEA	25 %–53 % binding	Oguz et al. (2022)
Glucomannan (Commercial Product)		13 %–21 % binding	
β-glucan from Red yeast *Sporidiobolus pararoseus* KM281507		99 % reduction	Tapingkae et al. (2022)
κ-carrageenan		40 % reduction	López-Ruiz et al. (2023)
Glucomannan	Fumonisins	26 %–34 % binding	Oguz et al. (2022)
Glucomannan (Commercial Product)		30 %–32 % binding	
Glucomannan	T-2	17 %–37 % binding	
Glucomannan (Commercial Product)		21 %–32 % binding	
β-glucan from Red yeast *Sporidiobolus pararoseus* KM281507		59.10 % binding	Tapingkae et al. (2022)
Glucomannan	HT-2	31 %–44 % binding	Oguz et al. (2022)
Glucomannan (Commercial Product)		22 %–55 % binding	
Glucomannan	DON	30 %–67 % binding	
Glucomannan (Commercial Product)		28 %–29 % binding	
β-glucan from Red yeast *Sporidiobolus pararoseus* KM281507		72.87 % binding	Tapingkae et al. (2022)

hindgut of the termite *Mastotermes darwiniensis*, detoxifies OTA by cleaving the phenylalanine moiety from the isocoumarin derivative, thereby converting it to the less toxic OTα. This fungus also detoxifies ZEA by opening the macrocyclic ring at the carbon end (Molnar et al., 2004; Murugesan et al., 2015). Additionally, *Sphaerodes mycoparasitica* SMCD 2220–01 converted ZEA and DON into less toxic metabolites by sulphating them through enzymatic biotransformation, resulting in reductions of 97 % and 89 %, respectively (Kim & Vujanovic, 2017).

β-glucans and mannan oligosaccharides in yeast cell walls act by binding mycotoxins (Shetty & Jespersen, 2006). Furthermore, as the level of β-d-glucan in the yeast cell wall increases, mycotoxin binding capacity increases (Yiannikouris et al., 2004). It was reported that *Saccharomyces cerevisiae* yeasts (6 strains) adsorbed AFB1, ZEA, DON, FB1-FB2 and T-2 mycotoxins by 22 %–74 % (Chlebicz & Śliżewska, 2020), and red yeast *Sporidiobolus pararoseus* KM281507 adsorbed AFB1, OTA, ZEA, DON and T-2 mycotoxins by 59 %–99 % (Tapingkae et al., 2022).

The protective effects of *Pichia kudriavzevii* and *Saccharomyces cerevisiae* RC016 yeasts against AFB1-induced toxicity in broiler chickens (Ali, Khatoon, et al., 2021; Poloni et al., 2020), distillers yeast sludge, a by-product of molasses fermented with *Saccharomyces cerevisiae*, was reported to have ameliorative effects against AFB1 toxicity. However, it was observed that the harmful effects continued in chickens consuming 600 μg/kg AFB1 (Khatoon et al., 2024).

2.3.3. Enzymes

Laccase and manganese peroxidase enzymes, which are ligninolytic enzymes formed by *Pleurotus ostreatus* fungus, were observed to reduce the toxicity of AFB1 by cleaving its lactone ring (Das et al., 2014). Recent studies on the reduction of mycotoxins by using enzymes from biological control methods are summarized in Table 6. *Phanerochaete sordida* YK-624's manganese peroxidase converted AFB1 to a less toxic metabolite (Wang et al., 2011). AFB1 was biologically transformed via lactone ring opening, primarily through lipase activity in the extracellular lysate of *Pseudomonas putida* (Singh & Mehta, 2022). AttM enzyme from *Bacillus megaterium* HNGD-A degraded AFB1 by 94.66 % and reduced OTA and ZEA by 81.32 % and 67.82 %, respectively (Cheng et al., 2023). Enzymes porin and peroxiredoxin from *Acinetobacter nosocomialis* Y1 fully degraded AFB1, with porin also completely degrading ZEA and peroxiredoxin degrading 91.12 % of it (Adegoke et al., 2023).

The toxicity of FB1 depends on its main amine group, and deamination reduces its toxicity. *Exophiala spinifera* carboxyesterases convert FB1 into the less toxic amino polyol AP1 (Duvick, 2001). Fumonisin esterase hydrolyzes FB1 into less toxic metabolites HFB1 and pHFB1. The fumonisin esterase from *Komagataella phaffii* was safely used in pig, chicken, and turkey feed to mitigate fumonisin contamination (Rychen et al., 2018). It was first reported that OTA is hydrolyzed to OTα *in vitro* by carboxypeptidase A and α-chymotrypsin (Pitout, 1969). Later studies showed hydrolysis of OTA to OTα by protease A and pancreatin at rates of 87.3 % and 43.4 %, respectively, through metalloprotein activity (Abrunhosa et al., 2006). Ochratoxinase enzymes from *A. niger* strains hydrolyze the amide bond of OTA, achieving up to 85.1 % degradation to OTα (Dobritzsch et al., 2014; Zhao et al., 2020). The lactonohydrolase ZHD101 from *Clonostachys rosea* detoxifies ZEA by cleaving the lactone ring (Kosawang et al., 2014). Epoxidase enzymes detoxify trichothecenes by converting toxic epoxy groups into dienes, as seen with the transformation of DON to its deepoxy form (Schatzmayr et al., 2006; Takahashi-Ando et al., 2002). The CotA protein obtained from *Bacillus licheniformis* and *Bacillus subtilis* catalyzes the oxidation of AFB1 into less toxic metabolites, while recombinant catalase from *Bacillus pumilus* degraded AFM1 by 63.2 % (Guo et al., 2020; Liu et al., 2024; Subagia et al., 2024). Additionally, it has been reported that there is a 65 % similarity between laccase CotA obtained from *Bacillus subtilis* and CotA obtained from *Bacillus licheniformis* (Subagia et al., 2024). D-Ala-D-Ala carboxypeptidases (DacA and DacB) from *Bacillus subtilis* ANSB168 metabolize OTA to OTα by 47 %, reducing oxidative stress and organ damage in hens (Qing et al., 2021). Metalloendopeptidase from *Bacillus subtilis* also biodegraded OTA by 45.26 % (Orozco-Cortés et al., 2023). Enzymes from *Bacillus subtilis* strains YT-4 and YQ-1 degraded ZEA by 95 % and 25.63 %, respectively (Shi, Mwabulili, et al., 2024; Zhou et al., 2024). Finally, the TV-AFB1D enzyme from *Trametes versicolor* biodegraded 67.4 % of AFB1 (Yang et al., 2022).

Table 6
Mycotoxins removal percentage of different enzymes.

Enzymes	Target Mycotoxins	Effects	References
Metaloendopeptidase from *Bacillus subtilis*	OTA	45 % degradation in 1 h	Orozco-Cortés et al. (2023)
DacA-DacB from *Bacillus subtilis* ANSB168		47 % degradation in 18 h and decreasing toxic effect in laying hens	Qing et al. (2021)
AttM from *Bacillus megaterium* HNGD-A6		81.32 % degradation	Cheng et al. (2023)
Ochratoxinase from *Aspergillus niger* W-35		85.1 % degradation	Zhao et al. (2020)
Glycosyltransferase from *Bacillus subtilis* YQ-1	ZEA	25.63 % degradation in 48 h	Zhou et al. (2024)
ZENY from *Bacillus subtilis* YT-4		95 % degradation in 36 h	Shi, Mwabulili, et al. (2024)
Porin from *Acinetobacter nosocomialis* Y1		100 % degradation	Adegoke et al. (2023)
Peroxredoxin from *Acinetobacter nosocomialis* Y1		91.12 % degradation	
AttM from *Bacillus megaterium* HNGD-A6		67.82 % degradation	Cheng et al. (2023)
rCAT from *Bacillus pumilus* E−1-1-1	AFM1	63.2 % degradation in 12 h	Liu et al. (2024)
CotA laccase *from Bacillus licheniformis* ANSB821	AFB1	AFB1 biodegradation to its less toxic metabolites AFQ1 and epi-AFQ1	Guo et al. (2020)
CotA laccase *from Bacillus subtilis*		AFB1 biodegradation to its less toxic metabolites AFQ1 and epi-AFQ1	Subagia et al. (2024)
Lipase from *Pseudomonas putida*		85 % degradation in 24 h	Singh and Mehta (2022)
TV-AFB1D from *Trametes versicolor*		67.4 % degradation in 5 h	Yang et al. (2022)
Porin from *Acinetobacter nosocomialis* Y1		100 % degradation	Adegoke et al. (2023)
Peroxredoxin from *Acinetobacter nosocomialis* Y1		100 % degradation	
AttM from *Bacillus megaterium* HNGD-A6		94.66 % degradation in 72 h	Cheng et al. (2023)

2.4. Plant bioactive compounds

Botanicals, including essential oils, spices, herbs and crude extracts, are useful alternatives to biofungicides (Prakash et al., 2020). Plant defense systems contain bioactive compounds such as phenolics, alkaloids, terpenes, and organic acids, which are being explored as safe antifungal agents (Chen et al., 2023). Recent studies on the reduction of mycotoxins by using plant bioactive compounds are summarized in Table 7.

The effects of four phenolic acids and four essential oils on *A. parasiticus* were evaluated. Phenolic acids completely inhibited aflatoxin production at 20 mM, while *Rosmarinus officinalis* almost completely suppressed it. *Lavandin grosso* and *Origanum virens* also reduced aflatoxin levels (Lorán et al., 2022). The antifungal activity of ricinine, a cyanopyridone alkaloid from *Ricinus communis*, was evaluated against *A. flavus* and *A. niger*. MIC values were reported as 7.81 μL/mL

Table 7
Mycotoxins removal percentage of different plant bioactive compounds.

Plant Bioactive Compounds	Target Mycotoxins	Effects	References
Sidr honey, pumpkin honey, morigna honey, *Nigella sativa* honey	OTA	Amelioration of oxidative stress parameters and improvement of adverse changes in biochemical parameters in mice	Al-Eisa et al. (2023)
Silymarin		Amerilation of serum biochemical parameters and histological lesions in broiler chickens	Stoev et al. (2021)
Tannic acid		Amelioration of oxidative stress parameters, performance parameters, liver and kidney enzymes in broiler chicken	Zhang, Xi, et al. (2022)
Aframomum melegueta, Syzygium aromaticum, Xylopia aethiopica		Amelioration of biochemical and oxidative stress parameters, kidney enzymes and liver enzymes in broiler chicken	Bashir et al. (2024)
Phillygenin from *Forsythia suspensa*		Amelioration of biochemical parameters, oxidative stress and antioxidant enzymes in broiler chickens	Guo et al. (2022)
flavonoids of *Rhizoma drynaria*		Amelioration of gut microbiota, intestinal barrier function, lipid and bile acid metabolism and reduction of oxidative stress in broiler chicken	Huang et al. (2023)
Silybum marianum, Thymus vulgaris, Rosmaninus officinalis		Amelioration of biochemical parameters, growth parameters, oxidative stress and immune response in broiler chickens	Raei et al. (2022)
Rosmaninus officinalis		63.1 %–100 % inhibition	da Silva Bomfim et al. (2020)
Vaccinium myrtillus L. aqueous extracts		100 % inhibition in 2.8 mg/ml	Vamvakas et al. (2021)
Star anise essential oil		98 % inhibition	Abdel-Khalek et al. (2022)
Origanum majorana		100 % inhibition in 1 μl/ml	Chaudhari et al. (2020)
Ocimum dhofarense		93 % degradation	Velazhahan et al. (2024)
Heliotropium bacciferum		95 % degradation	
Zataria multiflora		92 % degradation	
Eclipta prostrata		75.8 % degradation	Al-Owaisi et al. (2022)
Hybanthus enneaspermus		76.7 % degradation	
Centella asiatica		72.3 % degradation	
Origanum vulgare		Amelioration of biochemical parameters, oxidative stress, antioxidant parameters, inflammatory markers and histological lesions in rabbits	Hassan et al. (2023)
Genkwanin from *Daphne genkwa*		Amelioration of biochemical parameters, oxidative stress and liver damage in rats	Ijaz et al. (2022)
Mentha arvensis		75 % degradation	Anjum et al. (2022)
	AFB2	80 % degradation	
Vaccinium myrtillus L. aqueous extracts		100 % inhibition in 2.2 mg/ml	Vamvakas et al. (2021)
Rosmaninus officinalis		82.3 %–100 % inhibition	da Silva Bomfim et al. (2020)
Silymarin	Aflatoxins, Fumonisins	Amerilation of serum biochemical, growth, oxidative stress parameters and histological lesions in broiler chickens	Armanini et al. (2021)
caffeic acid, chlorogenic acid, ferulic acid, p-coumaric acid	Aflatoxins	Inhibited at 20 mM concentration	Lorán et al. (2022)
Lavandin grosso, Lavandin abrial, Origanum virens, Rosmarinus officinalis		*R. officinalis* inhibited, *L. grosso* and *O. virens* decreased	
Nigella sativa		Amelioration of hematological and biochemical parameters and hepatoprotective effect in goats	Elfaki and Elkhair (2023)
Quercetin	FB1, FB2	Amelioration of reprotoxicity effect and oxidative stress in sertoli cells	Ma et al. (2024)
Lamium album	FB1	87 % reduction	Uwienza et al., 2023
	FB2	81 % reduction	
	FB3	90 % reduction	
	DON	44.39 %–96.41 % reduction	
	ZEA	49.38 %–89.71 % reduction	

for *A. flavus* and 15.62 μL/mL for *A. niger* (Saravana Kumar et al., 2022). The degradation rates of 100 μg/L AFB1 and 50 μg/L AFB2 of aqueous extracts of *Mentha arvensis* were 75 % and 80 %, respectively. It was reported that the by-products produced during the degradation reactions were less toxic than the parent mycotoxins (Anjum et al., 2022).

Plant extracts obtained from different parts of the plant by various extraction methods are complex mixtures showing antimicrobial and antifungal activity thanks to their bioactive components (Ingle et al., 2017). The effects of *Lamium album* extract on *Fusarium* species and their mycotoxins were investigated. *F. culmorum* and *F. proliferatum* were reduced by up to 30.59 % and 42.97 %, while ergosterol levels decreased by 88.97 % and 93.17 %. FB1, FB2, DON, and ZEA levels were reduced by 44.39–96.41 % (Uwineza et al., 2023). In another study, *Vaccinium myrtillus* L. aqueous extracts completely inhibited AFB1 and AFB2 production at 2.8 mg/mL and 2.2 mg/mL, respectively (Vamvakas et al., 2021).

Essential oils are natural, volatile and complex components obtained from various parts of plants by various methods such as steam distillation, hydrodistillation or solvent extraction (Mutlu-Ingok et al., 2020). The antimycotoxigenic effects of several plant essential oils have been demonstrated. *Thymus daenensis*, *Satureja khozistanica*, and *Satureja macrosiphonia* reduced AFB1 production, with aqueous extracts of *T. daenensis* showing the strongest effect (Gorran et al., 2013). *Rosmarinus officinalis* inhibited FB1 and FB2 by over 97 % at 300 μg/mL and up to 99.6 % at 600 μg/mL (da Silva Bomfim et al., 2015). *Curcuma longa* essential oil suppressed *Fusarium verticillioides* growth by 79.3 % and

reduced FB1 and FB2 by over 99 % (Avanço et al., 2017). Additionally, *Lavandula dentata*, *Laurus nobilis*, and *Salvia officinalis* essential oils inhibited OTA production by up to 97.89 %, with *Lavandula dentata* and *Laurus nobilis* showing higher efficacy at lower concentrations (Dammak et al., 2019). In another study, *Syzygium aromaticum* exhibited the highest antifungal and *anti*-conidiogenic activity against *Fusarium verticillioides*, while *Rosmarinus officinalis* was less effective (Achimón et al., 2021). *Rosmarinus officinalis* also inhibited AFB1 and AFB2 by up to 100 % at 100–250 μg/mL (da Silva Bomfim et al., 2020). In another study, star anise essential oil reduced AFB1 by 98 % and, combined with gamma irradiation, inhibited *A. flavus* and *A. parasiticus* in stored grains (Abdel-Khalek et al., 2022). Essential oils from *Heliotropium bacciferum*, *Ocimum dhofarense*, and *Zataria multiflora* degraded AFB1 by 95 %, 93 %, and 92 %, respectively, and showed antioxidant effects *in vivo* (Velazhahan et al., 2024). Additionally, *Eclipta prostrata*, *Hybanthus enneaspermus*, and *Centella asiatica* extracts degraded AFB1 by over 72 % (Al-Owaisi et al., 2022).

When essential oils interact with food components, their effectiveness decreases and, in this case, they should be used at higher concentrations to observe the same effect. Essential oils used at high concentrations can create a negative result in terms of the organoleptic properties of the food with the effect of the aroma in its content (Castro-Rosas et al., 2017). It has been reported that essential oils should be used in safe doses and otherwise may cause various toxication reactions (Sharma et al., 2020). Essential oils may lose efficacy due to volatility and environmental degradation; encapsulation techniques can mitigate this. In addition, since they are volatile, their effectiveness may decrease as a result of being easily affected by oxygen and temperature changes in the environment. For these reasons, encapsulation techniques can be used to prevent loss of effectiveness and stability of

Table 8
Mycotoxin control methods: reduction percentages, mechanisms and limitations.

Method		Target Mycotoxin	Reduction %	Mechanism	Limitations
Physical	Thermal and Non-Thermal	Total Aflatoxins	31 %–100 %	Thermal fragmentation, fragmentation of DNA and toxin structure due to irradiation effects, breaking of toxicity bonds and conversion to a less toxic form due to cold plasma effects, cavitation, and cell wall damage due to light energy and electrical pulses.	The resistance of mycotoxins to heat and the loss in sensory and nutritional value caused by exposure to high temperatures impose limitations on thermal methods. Limitations in non-thermal methods include effects dependent on the food matrix, equipment costs, the risk of colour change in food, and the need for product-specific validation
		AFB1, AFB2, AFG1, AFG2, AFM1	29 %–100 %, 73 %–99 %, 57 %–99 %, 69 %–92 %, 50 %–78 %		
		OTA	32 %–100 %		
		ZEA	51 %–97 %		
		DON	61 %–83 %		
	Mycotoxin Binders	Total Aflatoxins	71 %–98 %	Silicate binders adsorb toxins via surface adsorption with their SiO4 tetrahedron structures; they bind toxins in the gastrointestinal tract and eliminate them via faeces. Carbon-based adsorbents capture toxins through physical adsorption due to their porous structure. Synthetic polymers capture toxins through surface complexation, ion exchange, and hydrogen bonds. Dietary fibres bind toxins through their phenolic and polysaccharide structures; bioavailability is reduced.	Silicate binders have limited toxin specificity and may bind nutrients and vitamins, reducing nutritional value; they are also pH dependent. Carbon-based adsorbents have low selectivity and carry a risk of environmental toxicity. Synthetic polymers are costly and their use in foods is limited. Dietary fibres, on the other hand, have low stability, with their binding capacity depending on the type of dietary fibre.
		AFB1, AFB2, AFG1, AFG2	20 %–96 %, 91 %, 86 %, 89 %		
		OTA	17 %–95 %		
		ZEA	10 %–88 %		
		DON	10 %–72 %		
		Fumonisins	9 %–54 %		
		T-2	11 %–44 %		
		HT-2	10 %–49 %		
Chemical		Total Aflatoxins	81 %–100 %	Hydrolysis of the lactose ring, conversion to a less toxic form via decarboxylation, degradation of the rings responsible for toxicity using ozone, and degradation of toxins.	Loss of nutritional value, loss of taste and aroma, risk of residues, oxidation of fatty acids
		AFB1, AFB2, AFG1, AFG2	86 %–97 %, 32 %, 99 %, 41 %		
		OTA	52 %–84 %		
		ZEA	100 %		
		DON	100 %		
		Fumonisins	81 %–83 %		
Biological	Bacteria	Total Aflatoxins	71 %–95 %	Binding to the cell wall or enzymatic degradation; transformation of toxins into less toxic forms	Limited work in real food products, binding may be pH- and strain-dependent and reversible, enzyme stability is limited, large-scale applicability is costly
		AFB1, AFB2, AFG1, AFG2, AFM1	37 %–99 %, 46 %, 97 %, 95 %, 50–94 %		
		OTA	77 %–98 %		
		ZEA	57 %–100 %		
		DON	19 %–90 %		
		Fumonisins	62 %–88 %		
		T-2	42 %–61 %		
	Yeast and Fungus	Total Aflatoxins	65 %–80 %	Adsorption with β-glucan and mannan on the cell wall; enzymatic biotransformation	
		OTA	52 %–74 %		
		ZEA	13 %–99 %		
		DON	22 %–72 %		
		Fumonisins	26 %–74 %		
		T-2	17 %–69 %		
		HT-2	22 %–55 %		
	Enzymes	AFB1	67 %–100 %	Opening of the lactone/epoxide ring; reduction in toxicity as a result of hydrolysis of the amide bond and transformation into a less toxic form	
		OTA	45 %–85 %		
		ZEA	25 %–100 %		
Plant Bioactive Compounds		AFB2	80 %–100 %	Disruption of cell membrane integrity, suppression of toxin biosynthesis genes and antioxidant effect	Low stability, risk of affecting sensory properties at high doses, limited studies on mycotoxin reduction
		OTA	63 %–100 %		
		ZEA	49 %–89 %		
		DON	44 %–96 %		
		Fumonisins	81 %–90 %		

essential oils (Mutlu-Ingok et al., 2020). This technology preserves the sensory aspects of food by optimizing the quantities of bioactive substances through the controlled release of essential oils (Takma & Korel, 2019). It was observed that *Origanum majorana* essential oil encapsulated in a chitosan nanoemulsion completely inhibited both *A. flavus* growth and AFB1 production. In addition, the median lethal dose in mice was determined as 11.889 μl/kg (Chaudhari et al., 2020).

In studies conducted to examine the effects of essential oils and plant extracts on health, quercetin, a flavonoid, reduced the toxic effects of AFB1 (Ma et al., 2024), tannic acid, a polyphenolic acid, reduced the toxic effects of AFB1 (Zhang, Xi, et al., 2022), genkwanin, a flavonoid isolated from *Daphne genkwa* plant, reduced the toxic effects of AFB1 in rats (Ijaz et al., 2022), *Nigella sativa* reduced the negative effects of aflatoxins in goats (Elfaki & Elkhair, 2023), *Origanum vulgare* reduced the toxic effects of AFB1 in rabbits (Hassan et al., 2023) and a spice mixture consisting of *Aframomum melegueta, Syzygium aromaticum* and *Xylopia aethiopica* was reported to reduce the toxic effects of AFB1 in broilers (Bashir et al., 2024), Silymarin an extract of *Silybum marianum*, reduced the toxic effects of OTA in broiler chickens (Stoev et al., 2021), *Silybum marianum, Thymus vulgaris* and *Rosmarinus officinalis* reduced AFB1 toxicity in broiler chickens (Raei et al., 2022), silymarin reduced the toxic effects of aflatoxin and fumonisin in broiler chickens and improved meat quality (Armanini et al., 2021), *Rhizoma drynarian* flavonoids reduced the toxic effects of AFB1 in broiler chickens (Huang et al., 2023), phillygenin derived from *Forsythia suspensa* plant species reduced the toxic effects of AFB1 in broiler chickens (Guo et al., 2022) and *Nigella sativa*, moringa, sidr and pumpkin honeys reduced OTA toxicity in mice (Al-Eisa et al., 2023).

3. Limitations and safety concerns in methods for the detoxification of mycotoxins

There are certain limitations in methods aimed at reducing mycotoxins. Table 8 shows the reduction percentages, mechanisms and limitations of the methods. Although thermal methods applied in physical detoxification methods are suitable for the decontamination of some substances, high temperatures are required to reduce mycotoxins. This also limits their scope of application. Non-thermal methods applied in physical reduction methods, such as UV, electron beam, ultrasound, microwave irradiation, pulsed light, pulsed electric field, and cold plasma, have attracted increasing interest due to their potential to be environmentally friendly and safe. However, non-thermal methods also have some limitations. Firstly, the cost of industrial equipment, the energy requirements for implementing the systems, the limited penetration of reactive species into complex food matrices, the fact that the majority of studies focus on cereals, and the limited interest in foods with mycotoxin potential, such as fruit and vegetables, create limitations. Mycotoxin binders, while binding mycotoxins, carry the risk of also binding nutrients and vitamins. Additionally, carbon-based binders pose a risk of environmental toxicity.

Chemical detoxification techniques can reduce mycotoxin concentrations; nevertheless, their implementation is constrained by various limitations. Their efficacy is significantly influenced by the food matrix, and treatments frequently result in adverse impacts on flavor, color, or nutritional content. Ascorbic acid, tocopherols, phenolic compounds and unsaturated fatty acids found in food react with chemical detoxifiers, causing a loss of nutritional value. Thirteen ozone degradation products of AFB1 have been identified through ozonolysis. Although these byproducts exhibit significantly reduced toxicity, their conversion to the parent compound in the digestive tract is a concern because they are more bioavailable than the parent mycotoxins. Further research is needed to confirm the safety of ozonation products (Afsah-Hejri et al., 2020; Freire & Sant'Ana, 2018; Luo et al., 2013). Furthermore, certain procedures may produce degradation products with unidentified or lingering toxicity, hence posing safety issues. Regulatory restrictions and the high cost of large-scale implementation further limit their use in food processing.

Another reduction method, biological detoxification methods, is an environmentally friendly, low-cost potential detoxification method that produces fewer or non-toxic metabolites. Compared to the detoxification capabilities of fungi, bacteria have greater detoxification capabilities and tolerance to environmental stresses. Bacteria detoxify more rapidly and therefore have a wider range of applications. However, enzymes isolated from various microorganisms target the toxicity rings of mycotoxins by causing enzymatic degradation, converting them into less toxic or non-toxic metabolites. However, data on the cytotoxicity of degradation by-products in the literature is limited. APQ1, a conversion metabolite of AFB1, has been reported to be 18 times less toxic and 83 times less mutagenic than AFB1 (Popescu et al., 2022). Additionally, genotoxicity tests have indicated that it exhibits 80 times less toxicity than AFB1 (Subagia et al., 2024). It has been reported that DOM-1, one of DON's enzymatic biotransformation products, is non-toxic and reduces *Campylobacter jejuni* load by altering intestinal permeability (Ruhnau et al., 2021). Another enzymatic biotransformation product, 3-epi-DON, has been reported to be 50 times less toxic than the primary mycotoxin DON (He et al., 2015). OTα, the main conversion metabolite of OTA, is less toxic than OTA. One study reported that the concentration required for OTα to damage genetic material was 100 times higher than that for OTA (Föllmann et al., 1995). However, OTα has been reported to have genotoxic effects in HepG2 cells at a concentration of 2.7×10^{-8} mol/L (Alfonso et al., 2022). Further research is needed into the toxic effects of degraded metabolites. There is a need to clarify the degradation mechanisms and by-products of other major mycotoxins besides AFB1 and DON. Biological detoxification methods also have certain limitations. Although significant reduction percentages have been achieved in studies, their efficacy and safety in real foods need to be verified. It is also thought that microorganisms may interact with food content and affect reduction rates.

Another detoxification method, plant bioactive compounds, has been included in our review due to their antifungal and antimycotoxin effects against mycotoxigenic fungi. They offer advantages in terms of low cost and a wide range of applications. Furthermore, when used at appropriate concentrations, they contribute to extending the shelf life of foods. Furthermore, encapsulation processes are applied to maintain their stability and enhance their effect. There is limited data on the antifungal and antimycotoxin effects of these compounds. Moreover, their instability against environmental factors limits their use, and at high concentrations, they have the potential to impair the organoleptic quality of food components.

4. Conclusion

The prevention and detoxification of mycotoxins in food and feed have been significant areas of research interest due to the potential health risks associated with their consumption. However, it is important to recognise that completely preventing mycotoxin formation in food and feed is not realistic. The literature provides convincing evidence that integrated prevention by in combination of agronomy, biocontrol, and post-harvest management is the most reliable way to reduce mycotoxin risk. The complex nature of storage environments, combined with subpar harvesting techniques and poor storage practices by consumers, significantly raises the risk of contamination. Good Agricultural Practices (GAP), which include clean seed, crop rotation, balanced fertilization, irrigation to minimize plant stress, targeted insect and fungicide control, and timely harvesting, can help reduce infection pressure from mycotoxin-producing fungi such as *Aspergillus* spp. and *Fusarium* spp., thereby lowering the risk of toxins downstream. Additionally, improper transport conditions in the food industry worsen the problem, allowing mould to grow even after the food has left farms or processing facilities. Therefore, despite rigorous efforts to prevent mycotoxin contamination, this harmful issue remains a pressing concern that requires constant vigilance and management across the entire food supply chain. To

reduce the risk of mycotoxin development, implementing specific measures is essential. These include removing conditions that favour mycotoxin production, as well as applying pre- and post-harvest strategies. Although various scientific studies have focused on controlling mycotoxin-producing fungi, neutralizing or decontaminating existing mycotoxins, and preventing their absorption in the digestive system, practical application in the field or industry remains limited. Factors contributing to this include the lengthy nature of physical and chemical control methods, nutrient loss, limited effectiveness, and the high costs of equipment. Among these strategies, adsorption has shown particular promise due to its simplicity, high removal efficiency, and cost-effectiveness. While biological methods are more effective, specific, and environmentally friendly, research is ongoing to ensure that the resulting degradation products are not toxic.

Emerging many detoxification technologies offer useful additional tools, but the literature reveals consistent, critical gaps: methodological heterogeneity, over-reliance on spiked samples, insufficient toxicological follow-up on degradation products, and a shortage of industrial-scale studies. Until those gaps are filled, many "detoxification" claims should be treated cautiously. These are promising but not fully validated for routine use in food systems yet. Future research should focus on validating detoxification methods in real food systems and assessing the safety of degradation products.

CRediT authorship contribution statement

Kubra Deliklitas: Writing – original draft, Investigation, Conceptualization. **Cengiz Gokbulut:** Writing – review & editing, Supervision, Investigation.

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.

Data availability

Data will be made available on request.

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