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Identification and risk elimination of mycotoxins.

Emtenan M. Hanafi[1], Enas N Danial[2], Seham S Kasem,[3] Moetazza M Alshafei [3]& Walaa H. Khalifa[4]

[1] *Department of Animal Reproduction and A. L., Veterinary Research Institute, National Research Centre, Giza, Egypt*
[2] *Department of Chemistry of Natural and Microbial Product, Pharmacology Institute, National Research Centre, Giza, Egypt*
[3] *Department of Nutrition and Food Science, Food Industry and Nutrition Institute, NRC, Giza, Egypt.*
[4] *Department of Animal Production, Agriculture and Biological Research Institute. National Research Centre, Giza, Egypt.*

ABSTRACT

Background & Purpose:
To date, 50–80% of food contaminated with mycotoxins. More than 500 type of mycotoxins have been identified, produced by different types of fungi causing financial losses to agriculture and industry. The most hazardous mycotoxins for public health include aflatoxins (AF), fumonisin (FUM), ochratoxins (OTA), zearalenone (ZEN), and deoxynivalenol (DON) mainly produced by Aspergillus, Penicillium and Fusarium species. Mycotoxin contamination may occur in ripening cereals and other agricultural commodities before harvest and consequently contaminate livestock feed. Mycotoxins may also be found in animal source food like milk, eggs, cheese and meat. Several types of control measures were taken using physical, chemical and biological methods. This article reviews the incidence of mycotoxicosis in food chain in Egypt and the mechanisms of in vitro detoxification of food and animal feed products.

Key words: *Mycotoxin- Incidence- detoxification- Egypt*

INTRODUCTION

Mycotoxins are produced by several types of molds under specific conditions of high humidity, high temperature and poor agricultural practices, or contaminated and damaged crops [1,2]. Mycotoxins are largely lipophilic so they have the ability to become part of animal products such as milk which contains AFLM1 and can cause serious health problems [3]. Currently, more than 500 species of mycotoxins were identified and about 1000 types have yet to be discovered and under research [4].

The main types of mycotoxins contaminating animal feedstuffs are Aflatoxin B1 (AFB1), zearalenone (ZEN), deoxynivalenol (DON) and fumonisin B1 (FB1). They contaminate crops (like wheat, corn, barley, peanuts, peas, nuts) and forage [5]. The toxicity symptoms varies according to the type of mycotoxin (Table 1). AFB1 is the most toxic one which is produced by Aspergillums and known as the most carcinogenic one [6]. It causes hepatotoxicity, immunotoxicity, mutagenicity, carcinogenicity and teratogenicity for many animal species [7–9]. Other types of mycotoxins like DON, ZEN and FB1 are mainly produced by Fusarium molds [5,10].
DON can induce anorexia, vomiting, and disturb intestinal and immune functions in different animals. It inhibits the synthesis of nucleic acids and proteins [11,12]. ZEN causes infertility and reproductive disorders in livestock because it has a similar structure to 17 β-estradiol and competes for estrogen receptor binding [13–15]. FB1 (fumonisin) can cause toxicity to both liver and kidney. It also causes neurotoxicity, immunotoxicity and cancer in humans and animals [16].

It was recorded that about 25% of the world's cereals are contaminated with mycotoxins and consequently in processed food made from the contaminated materials, and they can also occur in milk, meat, and eggs when animals ingest these mycotoxins [22]. This review was for screening the incidence of mycotoxin in crops, meat and dairy products, and the applied methods for control.

Corresponding author emails: walaahussein10@gmail.com (Walaa H. Khalifa)
Enas_mahdy@yahoo.com (Enas N Danial)
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Table 1: Molds, mycotoxins, toxicity symptoms.

Mold	Mycotoxin product	Toxicity symptoms	Reference
Aspergillus flavus Aspergillus parasiticus	**Aflatoxin AFB1,AFB2**	**Reduced feed intake, Reduced milk yield, Immunosuppression et al.,2022Reproductive effects Hepatotoxicity, Nephrotoxicity and Gastroenteritis**	**[6, 7, 3, 17]**
Fusarium verticillioides, Fusarium *nyagamai,*, Fusarium *oxysporum*,	**DON (Deoxy-nevalenol)**	**Reduced feed intake, Reduced milk yield, carcinogenic**	**[18, 11, 12]**
Fusarium Verticillioides, Fusarium Moniliform, Fusarium Proliferatum	**FB1 (Fumonsins)**	**Reduced feed intake, Reduced milk yield, Hepatotoxicity, Nephrotoxicity**	**[19, 16]**
Aspergillus westerdijkiae Penicillium nordicum Penicillium verrucosum	**OTA (Ocratoxin)**	**Reduced feed intake, Reduced milk yield and Gastroenteritis**	**[20, 1, 2]**
Fusarium graminearum	**ZEN (zeralenone)**	**Reduced feed intake, Reduced milk yield, Reproductive effects and Gastroenteritis**	**[21, 15, 13, 14]**

2. INCIDENCE OF MYCOTOXICOSIS:

2.1. Crops

2.1.1. Wheat

Wheat is the most consumable food grain worldwide. It is contaminated with several mycotoxins (Table 2) including aflatoxins (AFs), ochratoxin A (OTA), and Fusarium toxins [23]. Research study in Egypt, detected AFB1 in wheat grain samples in different governorates (table 2) recording the highest concentration (35.21 to 49.79 µg/kg) in Giza. Also AFG1 recorded the highest level (41.38 and 30.41) in Giza and Elfayoum, respectively [24] while, it should not exceed 4 µg/kg according to the European Commission [25] and Egyptian Organization for Standardization and Quality Control [26]. It was reported that these wheat samples were unfit for human consumption.

Table 2: Concentration of mycotoxins in wheat in some governorates of Egypt.

Governorate	District	Mycotoxin concentration (ug/kg)				
		AFB1	AFB2	AFG1	AFG2	OTA
Cairo	Helwan	0.19	0.09	9.98	7.12	limited
	Almaadi	0.13	Limited	4.16	4.87	limited
	Elshoruq	limited	0.09	4.10	0.23	1.37
Aelxandria	Al Manshieh	limited	Limited	16.29	3.13	limited
	Alajami	limited	1.47	16.37	3.17	limited
	Abukir	limited	0.12	12.05	8.14	limited
Giza	Alomraniyah	35.2	1.94	21.71	1.03	limited
	Dokki	limited	0.22	41.38	2.05	limited
	Atfih	49.8	2.96	10.67	0.20	limited
Elfayoum	Sinnuris	Limited	1.93	20.77	1.48	limited
	Ibshway	Limited	2.44	30.41	1.18	limmited
	Etsa	limited	limited	13.71	3.28	0.21

2.1.2. Maize and rice

The collected maize and rice samples from different localities of Egyptian market were found contaminated by 23 species of fungi. About 70% of the collected samples were infected with Aspergillus flavus and niger (33%, 40% recovered from maize and 46%, 27% recovered from rice, respectively). Total aflatoxins and fumonisins were estimated in maize samples as 9.75 and 33 mg/kg respectively, while in rice samples averaged 5.15 and 1014 mg/kg respectively [27].

The rice samples collected from different governorates of Egypt and kept in cloth bags and stored at ambient environmental conditions showed elevated moisture content in both dehulled and hulled rice stores, especially in Sharkia governorate (Table 3); this may refer to the quality of soil and the service during agriculture [28]. It was also noticed that the brown rice collected for processing from zero to 90 days was free of aflatoxins, while

during the period from 180 to 270 days it had varieties of aflatoxin. The hulled rice had the highest value of aflatoxin specially in Sharkia, followed by Dakahlia, and the lowest level of aflatoxin were in hulled rice in Kafr El-Sheikh. After 180 days of storage, it was grade 3 and infested by fungi from all the collection zones (Dakahlia, Kafr El-Sheikh, and Sharkia) [29].

Climate change has emerged as a significant driver influencing the distribution, frequency, and severity of mycotoxin contamination in crops and food systems. Rising global temperatures, increased humidity, drought stress, and shifting rainfall patterns have collectively contributed to an expansion of fungal growth zones and extended growing seasons for mycotoxigenic fungi such as Aspergillus, Fusarium, and Penicillium [30, 31].

Recent studies demonstrate that aflatoxin contamination in maize and peanuts increases significantly during drought events followed by high humidity periods [32]. These findings underscore the urgent need to integrate climate-resilient agricultural practices, early warning systems, and mycotoxin management strategies into national and international food safety frameworks.

Table 3: Fungus count and Aflatoxin level in rice during storage

	Dakahlia	Kafr-Elshikh	Shrakia
Humidity %	**15**	**15**	**16.5**
Count of fungi for hulled rice			
Zero time	**1.9**	**1.8**	**0.4**
Storage 90 days	**3**	**3.1**	**2**
Storage 180 days	**3.21**	**3.24**	**1.5**
Level of Aflatoxin in stored rice			
After 180 days	**1.2**	**1**	**1.4**
After 270 days	**2**	**1.5**	**2.7**

Evaluation of the prevalence of toxigenic fungi in barley grains, white and yellow corn, rice, and wheat samples (Table 4) showed that there is variable fungal colony count in different governorates of Egypt. Aspergillus spp. were the predominant fungi followed by Penicillium spp. The HPLC analyses revealed that fungal isolates produced the four types of aflatoxins: AFB1 (0.02–875.03 ng/g), AFB2 (20.07–13.55 ng/g), AFG1 (0.06–2.85 ng/g), and AFG2 (0.71–89.29 ng/g). These results indicated the importance of a control system to regulate fungal contamination and mycotoxin production in grains before consumption [33].

Table 4 Total mold count in different grains in different governorate of Egypt

(Cfu/gm)	Barley	White corn	Yellow corn	Rice	Wheat
Alexandrea	17	18	23	15	22
Beheira	14	9	21	14	17
Cairo	14	13	14	10	18
Giza	15	17	17	13	23
Menoufia	8	12	15	10	14
Qalyubia	9	14	9	10	11

2.1.3. Silage

Silage samples collected from Assiut and Sohag governorates in Egypt were highly contaminated with different genera and species of molds. With total count of viable mold 9920 and 131,600 colonies/gm dry silage on each of Sabouraud's dextrose agar and glucose–Czapek's media, respectively. The most prevalent genera were Aspergillus (100% and 57.5% of the samples), Penicillium (55%and 100%) on the two mentioned media, respectively. Also, Gibberella fujikurori and Fusarium oxysporum were present in moderate incidences. Mycotoxin incidence were also determined and the highest prevalence (22.5%) was for Aflatoxins in all analyzed samples [34].

2.2. Meat Products

Meat products may have the mycotoxin residue from feeding live animals contaminated feed and may be from using bad quality flavoring materials, particularly spices, and improper hygienic procedures during processing and storage of the products. Mold contamination of meat products is a major public health hazard as causing

three different types of illnesses, namely mycosis, mycotoxicosis, and allergy [35]. The most toxic mycotoxins commonly found in meat are ochratoxin A (OTA) and aflatoxin B1 (AFB1). Meat products, such as liver, fermented sausages, dry rack & blade, pancetta, bacon, ham, etc., are consumed worldwide, and the consumers ask for higher-level quality and safety of these products. Table (5) showed high prevalence of mold in minced meat and sausage [35] among meat products in local market of Egypt.
Spices added to meat products are usually contaminated [36]. High AFB1 was demonstrated in paprika (155.7 µg/kg) [37] and black pepper (75.8 µg/kg) [38]. The same was for OTA in Paprika (177.4 µg/kg) [39]; and black pepper (79.0 µg/kg) [40]. OTA was found in dry-fermented sausages (8.11 µg/kg) spiced in red paprika [41]. Also, prosciutto samples showed higher level of OTA due to pepper spiking; namely, pepper often becomes contaminated with Aspergillus moulds, especially *A. Niger*, which produces OTA [42].

Table 5: Incidence of mold count in meat products in Egypt during 2020-2021

Meat product	Mold count (Cfu /gm)	references
Minced beef meat	$2.5\times10^2 \pm 1.6\times10^2$	43
Beef burger	$1.3\times10^3 \pm 9.2\times10^2$	44
sausage	$3.4\times10^2 \pm 2.1\times10^2$	35
Beef luncheon	$2.3\times10^2 \pm 1.3\times10^2$	45
Frankfurter	$0.6\times10 \pm 0.2\times10$	46
Kofta	$0.5\times10 \pm 0.1\times10$	47
Bastirma	$0.4\times10 \pm 0.07\times10$	48

2.3. Dairy Products

Dairy products are a vital component of the human diet, especially for infants and young children, as they are a rich source of essential nutrients. However, their nutrient richness and moisture content create an ideal environment for molds [49]. Mold growth in dairy products depends on temperature, humidity, pH, and composition. While molds are not pathogens, they can produce mycotoxins, the most prevalent of which is Aflatoxin B1 [50]. AFB1 ingested by lactating animals is converted into AFM1 in the liver [51] and excreted in milk, where it binds to casein and remains in dairy products, especially cheese [52]. AFM1 is highly persistent, even during pasteurization and UHT treatment [53, 54]. Due to its toxicity, over 60 countries have established permissible limits [55]. EU regulations cap AFM1 at 50 ng/L, while the US allows 500 ng/kg [56]. Prolonged exposure may cause immunosuppression, hepatocarcinoma, and impaired child growth due to AFM1 interaction with DNA [57]. Table (6) showed AFM1 prevalence in milk (the highest prevalence was for goat milk) and milk products (the highest prevalence was for Ras cheese) and showed the effect of different treatment of milk on the prevalence of AFM1 (the highest prevalence was for pasteurized milk) [58-70].

Table 6: of AFM1 and Mold Contamination in Dairy Products

Product Type	Source / Processing Type	AFM1 Prevalence (%)	Mold Contamination (%)	Mean Mold Count (CFU/g)	Ref No
Milk	Goat	84.5%	15–28%	$1.9\times10^3 – 2.6\times10^6$ CFU/ml	60
Milk	Cow	78.2%	12–25%	$1.08\times10^4 – 3.15\times10^6$ CFU/ml	61
Milk	Sheep	60.2%	10–22%	$1.5\times10^3 – 3.2\times10^3$ CFU/ml	62
Milk	Camel	56.0%	9–20%	~1.9×10^5 CFU/ml	63
Milk	Pasteurized	99.5%	<2%	$2.0\times10^3 – 3.0\times10^3$ CFU/ml	64
Milk	UHT	91.3%	≈0%	$0 – 10^5$ CFU/ml	61
Milk	Raw	73.0%	9–12.6%	$10^4 – 10^6$ CFU/ml	65
Cheese	White	95.7%	64–88%	$1.2\times10^3 – 1.3\times10^4$ CFU/g	66
Cheese	Traditional	86.7%	68–76%	$3.6\times10^3 – 6.5\times10^3$ CFU/g	66
Cheese	Feta	66.5%	54–76%	1.2×10^3 CFU/g	66
Cheese	Cheddar	19.3%	40–65%	~2.0 $\log_{10}$ CFU/g	67
Ras Cheese	Semi-hard ripened cheese from raw or pasteurized cow milk	80–100%	73.3%	$12 \times 10^4 \pm 7.5 \times 10^4$ CFU/g	68
Flavored Yogurt	Sweetened/flavored yogurt from pasteurized milk	35–60%	56.6%	$49 \times 10^3 \pm 18 \times 10^3$ CFU/g	69
Cheese Analogue	Processed cheese with vegetable oils and milk powder	28–55%	50.0%	$2.9 \times 10^2 \pm 2.3 \times 10^2$ CFU/g	70
Plain Yogurt	Natural yogurt from pasteurized milk	30–72%	46.7%	Not reported	66

Milk-based Cereals	**Infant cereals with milk powder**	**20–43%**	**46.7%**	**Not reported**	**71**
Milk Powder	**Dried cow milk (imported or local)**	**48–88%**	**40.0%**	**Not reported**	**72**
Cream Analogue	**Dairy cream substitute with vegetable oils**	**18–42%**	**33.3%**	**4.5 × 10 ± 1.1 × 10 CFU/g**	**70**

3. MYCOTOXINS REDUCTION & DETOXIFICATION

Mycotoxins can be reduced or eliminated through physical, chemical, and biological strategies.

3.1. physical methods

3.1.1. Specific gravity of the mycotoxins Contaminated cereals have lower specific gravity than the normal ones. These characteristics enable gravity separation, sieving and aspiration techniques for isolation of the mycotoxins contaminated feedstuffs [71,72]. However, these techniques are suitable for small-scale applications.

3.1.2. Washing

Mycotoxins can be isolated and decontaminated according to its solubility either in water or fat by extraction either by washing in water or organic solvent [73]. However, these methods causes loss of nutrients, and costly due to drying and toxic extracts disposal, which limit their large-scale application.

3.1.3. Thermal treatment

Despite thermal treatment was used for mycotoxin detoxification for many years. AFB1, DON, ZEN and FB1 are heat-stable compounds needs very high temperature for decomposition, 237, 175, 220, 150 °C, respectively which makes it difficult to eliminate [74-76].

3.1.4. Irradiation

Irradiation was used for removing mycotoxins from the feed on an industrial scale. It can be classified into ionizing (x-rays, γ-rays and electron beam) and non-ionizing radiations (ultraviolet rays, infrared and microwave) [77, 78]. Although irradiations can decontaminate mycotoxins in feedstuffs, it may generate harmful microorganisms and affect the nutritional values of feedstuffs.

3.1.5. Adsorption binders

Some compounds such as bentonite, montmorillonite, zeolite, hydrated sodium calcium alumino silicate, kaolin, and illite can form a complex with mycotoxins, to hinder absorption of mycotoxins from the gastrointestinal tract into the blood and organs of animals [79].

They are effective at removing mycotoxins from the feed with more than 90% efficiency.

Glucomannan is a strong adsorbent to toxic substances and harmful pathogenic bacteria in animals. It has binding ability for AFs, ZEN, FBs, and DON by 95%, 75%, 59% and 12%, respectively [80,81].

The β-D-glucan chains of yeast cell walls have been demonstrated to effectively inactivate ZEN [82, 83].

Inactivated yeast cell walls fermenting volatile organic compounds could decrease AFs and DON synthesis by 82% and 93%, respectively, in vitro [84].

Activated charcoal has excellent adsorption capabilities in aqueous environment and can reduce AFs, ZEN, DON due to its porous structure [85, 86]

3.1.6. Magnetic carbon Nano composites

Produced by maize wastes for the removal of AFB1, with adsorption percent 90% within 180 min at pH 7.0 [87]. In addition, cross-linked chitosan-glutaraldehyde polymers could adsorb multiple mycotoxins such as AFB1 (73%), ZEN (94%) and FB1 (99%), but no obvious adsorption for DON and T-2 toxin (< 30%) [88].

3.1.7 Lactic acid bacteria and yeast

Yeast and LAB, cell wall contain peptidoglycan, proteinaceous layer, and polysaccharides. These cell wall components make adhesion to macromolecules of toxic compounds. Lactobacillus casei, Bifidobacterium longum, Lactobacillus mesenteroides and Lactobacillus rhamnosus can significantly reduce the absorption of aflatoxin in the intestinal tract [89]. Lactobacillus plantarum F22 had a strong adsorption capacity on AFB1 and the adsorption rate could reach 56.8% [90]. Lactobacillus plantarum B7 and Lactobacillus pentosus X8 can remove 52.9% and 58.0% of FB1 [91]

3.2. Chemical methods

3.2.1. *Alkaline treatment*

Alkalines such as sodium hydroxide, ammonia, potassium hydroxide and sodium carbonate were used for the destruction of mycotoxins in the moldy feedstuffs [92, 93]. The lactone ring of AFB1 can be broken by base hydrolysis to produce coumarin sodium salt then eliminated by washing with water [94]. Despite the detoxification of mycotoxins, other forms of masked toxins were formed by this reaction with possible harmful side effects on the environment and food quality (changes in nutritional value, texture, or flavor) [92, 93].

3.2.2. *Ozone treatment*

The oxidizers such as hydrogen peroxide, ozone, sodium and calcium hypochlorite, chlorine and other oxidizers were used for detoxification and degradation of AFs, DON, ZEN and FB1 and showed very satisfactory effect [95].

3.3. Biological methods

Mycotoxin biodegradation takes place by the secondary metabolites produced by the organism either intracellular or extracellular and change the toxic group of the mycotoxin molecules to non-toxic or less toxic degradation products [96].

3.3.1. *Microbial biotransformation against AFB1*

Fungal strains like S. cerevisiae ŁOCK 0119 have the ability to degrade AFB1 at levels of 69.0% [97]. Also, various Aspergillus strains like A. niger RAF106 and A. niger FS10 can degrade AFB1 to levels between 88.6% and 98.7% [98, 99].

Bacterial strains such as Nocardia, Flavobacterium aurantiacum, and Corynebacteroids secrete enzymes to degrade 74.5% of AFB1 within 24 hours [100, 101, 102].

Bacillus is an important class of bacteria with the ability to degrade AFB1. Bacillus subtilis UTBSP1 showed a degradation rate of 78.4–95.0% [103]. Another strain, Bacillus subtilis ANSB060, could degrade 81.5% of AFB1 within 72 h [104]. Other Bacillus strains such as B. velezensis DY3108, B. licheniformis CFR1, B. shackletonii L7, and B. subtilis JSW-1 showed degradation levels between 67.2–94.7% [105, 106, 107, 108].

Other bacteria such as Pseudomonas putida, Escherichia coli CG1061, Stenotrophomonas sp. CW117, and lactic acid bacteria also showed efficient biodegradation rates up to 90% or more for AFB1 [109, 110, 103].

3.3.2. *Microbial biotransformation against DON*

Some bacteria isolated from soil samples (Devosia insulae A16, strain E3-39, bacterial consortium C20, Pseudomonas sp. Y1, and Lysobacter sp. S1) converted DON to 3-keto DON or 3-epi-DON, which are less toxic derivatives [111, 110, 112]. These strains showed 74–100% DON reduction [111, 110, 113]. Other isolates like LS100, SS3, strain BBSH 797, and Eggerthella sp. DII-9 showed high biotransformation of DON to diepoxy-deoxynivalenol [104, 114, 115].

Strains of Aspergillus (NJA-1) and Bacillus subtilis ASAG 216 decreased DON concentrations by 81.1% and 94.4%, respectively [116, 117].

3.3.3. *Microbial biotransformation against ZEN*

Microorganisms like Bacillus natto and Bacillus subtilis detoxify ZEN to α-zen, β-zen, sulfate, and other low- or non-toxic secondary products with over 75% efficiency. Another study reported detoxification of ZEN by B. subtilis strain up to 99% [118].

Bacillus subtilis ANSB01G, isolated from broiler intestine, degraded 88.7% of ZEN in infected corn grain [119]. Bacillus pumilus ES-21 and Bacillus amyloliquefaciens ZDS-1, isolated from soil, showed 95.7% ZEN reduction [120, 121].

3.3.4. Microbial biotransformation against Fumonisin B1 (FB1)

Some fungal and bacterial microorganisms can detoxify fumonisins. The yeast Saccharomyces cerevisiae IS1/1 can degrade 45–50% of FB1 and FB2 in culture medium. S. cerevisiae SC82 degrades 22% of FB1 and 25% of the FB1–FB2 mixture [122].

Three strains of Bacillus spp. S9, S10, and S69 degraded 43%, 48%, and 83% of FB1, respectively [123].Bacterial strain NCB1492, isolated from soil, degraded 100% of FB1 at 25°C after 24h [124].Another study reported 100% degradation of FB1 by bacterial consortium SAAS79 [125].

3.3.5. The usage of catabolizing enzymes

Microbial enzymes have been widely studied for their ability to degrade mycotoxins into less toxic or non-toxic metabolites (Table 8). Probiotics can detoxify the toxic compounds through mechanisms such as reducing ion exchange, microprecipitation, chelation, and adsorption [126, 127]. Mycotoxins can be degraded by some microorganisms and their toxic metabolites in GIT of animals [128, 129]. The microbial enzymes that can detoxify FB1, DON, ZEN and AFB1 showed high efficiency.

Table 7: Comparison of Mycotoxin Detoxification Methods

Category	Method	Mechanism	Effectiveness	Cost	Impact on Food Quality	Industrial Applicability	Ref
Physical	**Specific gravity separation**	**Separation of contaminated grains based on density**	**Moderate**	**Low**	**Minimal**	**Low (small scale)**	**[71], [72]**
	Washing (water/solvents)	**Extraction of soluble mycotoxins**	**Moderate**	**High**	**Nutrient loss**	**Limited due to cost and waste**	**[73]**
	Thermal treatment	**Heat-induced degradation of mycotoxins**	**Low to moderate**	**Moderate**	**Possible quality degradation**	**Limited**	**[74], [75], [76]**
	Irradiation	**Chemical bond disruption via radiation**	**High**	**High**	**May reduce nutritional value**	**Moderate to high**	**[77], [78]**
	Adsorbent binders (e.g. clay)	**Binding toxins in the gut to prevent absorption**	**High (>90%)**	**Moderate**	**No direct food effect**	**High (used in commercial feeds)**	**[79], [80], [82-86],**
	Magnetic nanocomposites	**Nanomaterial adsorption of toxins**	**High**	**High**	**Low impact**	**Experimental**	**[87] [88],**
	Probiotic yeast/LAB	**Toxin binding in gut or food surface**	**Moderate**	**Moderate**	**Can improve animal gut health**	**Under industrial development**	**[89], [90] [91]**
Chemical	**Alkaline treatment**	**Chemical breakdown of mycotoxins (e.g., AFB1)**	**High**	**Low**	**May affect taste/texture**	**Possible with quality monitoring**	**[92], [93] [94]**
	Ozone & oxidizing agents	**Oxidation of toxin functional groups**	**Very high**	**Moderate**	**Potential quality alteration**	**High (under strict conditions)**	**[95]**
Biological	**Microbial degradation**	**Enzyme production that transforms toxins**	**High (70–100%)**	**Low to moderate**	**No or positive effect**	**Highly promising (scalable potential)**	**[96], [97], [103], [110]**
	Nutritional	**Reduce oxidative stress caused by mycotoxin**	**High**	**Low**	**Positive effect**	**promising**	**[143, 163]**

3.3.5.1. Catabolizing enzymes against AFB1

Laccase while oxidase can detoxify FB1 [128]. The detoxification enzyme for AFB1 designated as aflatoxin detoxifizyme significantly reduced its mutagenic effects [130].

Manganese peroxidase (1.5 U/mL) can degrade 90% of AFB1 after 2 days of reaction [131]. Bacillus shackletonii L7 and Myxococcus fulvus ANSM068 produce aflatoxin AFB1 detoxifying enzyme [107, 132].

3.3.5.2. Catabolizing enzymes against DON

Many studies showed that DON can be degraded to less toxic compounds by enzymes like NADH-dependent bacterial cytochrome P450, peroxidase such as manganese peroxidase and lignin peroxidase, Aldo-keto reductase DepA and DepB [133], and a quinone-dependent dehydrogenase and two NADPH-dependent aldo/keto reductases (AKR13B2 and AKR6D1) [134].

3.3.5.3 Catabolizing enzymes against ZEN

Mycotoxin ZEN can be degraded by laccases, copper-containing oxidases used in many industrial applications [135, 136]. A recombinant ZEN-specific lactonohydrolase was innovated and secreted into the culture liquid from transformed fungal clones and removed ZEN from the field [137].

Another development of a recombinant fusion enzyme produced by two single genes (ZEN-specific lactonohydrolase and carboxypeptidase) was successful in complete degrading of ZEN to the non-toxic product in 2 h at pH 7 and 35 °C [138].

3.3.5.4. Catabolizing enzymes against FB1

FB1 can be degraded to a less toxic substance by fumonisin carboxyl esterase Fum D enzyme when incubated for 2 h in the GIT of turkeys and pigs [139, 128].

Table 8: Catabolizing Enzymes for Degradation of Major Mycotoxins

Mycotoxin	Enzyme Type	Source/Organism	Detoxification Efficiency	Reference
AFB1	Laccase	Fungi	Degrades AFB1	128
AFB1	Aflatoxin detoxifizyme (recombinant)	Armillariella tabescens	Reduces mutagenicity	129
AFB1	Manganese peroxidase (1.5 U/mL)	—	Degrades 90% of AFB1 in 2 days	130
AFB1	AFB1-degrading enzymes	Bacillus shackletonii L7, Myxococcus fulvus ANSM068	High AFB1 detoxification	131 132
DON	Cytochrome P450 (NADH-dependent)	Bacteria	Converts DON to less toxic compounds	133
DON	Manganese & lignin peroxidase	Bacteria	Degrades DON	134
DON	Aldo-keto reductases (Dep A, Dep B)	Bacteria	Reduces toxicity	134
DON	AKR13B2, AKR6D1 (NADPH-dependent)	Bacteria	Effective DON biotransformation	134
ZEN	Laccases	Fungi	Industrial degradation of ZEN	136 135
ZEN	Lactonohydrolase (recombinant)	Transformed fungal clones	ZEN removal from culture	137
ZEN	Fusion enzyme (lactonohydrolase + carboxypeptidase)	fungus	Complete degradation of ZEN within 2 h at pH 7, 35°C	138
FB1	Oxidase	GIT flora	Degradation activity against FB1	128
FB1	Fumonisin carboxylesterase (FumD)	GIT flora	Degrades FB1 in 2 h in pig and turkey GIT	139

3.4. Nutritional Strategies for Mycotoxin Detoxification

Mycotoxins are known to impair nutrient uptake and induce the generation of free radicals, which in turn cause cytotoxicity. Nutrients that stimulate the synthesis of glutathione (derived from glutamate, cysteine, and glycine) [141-143] or enhance antioxidant enzyme activity, can support detoxification. (Table 9).

In addition to well-known antioxidants like selenium and vitamins, studies have highlighted the protective effects of several other natural and synthetic compounds. For example, butylated hydroxytoluene (BHT) reduces the toxicity of AFB1 by stimulating glutathione S-transferase activity while inhibiting CYP450 activity [144]. Alpha-lipoic acid has shown hepatoprotective effects and improved growth in broilers exposed to AFB1 [145].

Bioactive peptides such as lactoferrin, plant defensins, antimicrobial peptides, and active yeast have shown protective effects against DON toxicity in piglets, improving antioxidant and immune markers. Furthermore, Xiao et al. reported that a composite nutrient mixture improved performance, intestinal function, and immune response in weaned piglets exposed to DON [146].

Natural antifungal agents such as citral, citric acid, and cinnamaldehyde have shown the ability to disrupt fungal cell membranes, inhibit DNA/protein synthesis, and induce lethal genetic damage in Aspergillus flavus, thereby reducing aflatoxin production [147-149].

Economic Impact and Practical Applications for Mycotoxin Management

Mycotoxin contamination poses a serious economic challenge to both global and local agricultural and food systems, including in countries like Egypt. These toxic metabolites, produced by fungi, result in reduced crop yields, compromised livestock productivity, and substantial post-harvest losses. According to the Food and Agriculture Organization (FAO), up to 25% of the world's food crops are contaminated with mycotoxins annually, causing economic losses exceeding $1.5 billion in the United States alone, with even more severe consequences in developing countries where monitoring and control measures are often inadequate. In Egypt,

for instance, the rejection of imported wheat shipments due to excessive aflatoxin levels has disrupted supply chains and increased dependence on foreign grain markets**.**

In the livestock industry, animals consuming contaminated feed may experience poor feed conversion, suppressed immune function, reproductive issues, and increased mortality, which not only reduces productivity but also escalates veterinary costs and management burdens. Additionally, dairy and meat exports may face bans if they surpass global safety thresholds for mycotoxins, leading to further economic losses and market exclusion. Industries involved in food processing and distribution also bear the financial strain of routine testing, detoxification treatments, product recalls, and compliance with safety standards, all of which reduce profit margins and contribute to higher food prices, affecting both producers and consumers.

Table 9: Nutritional Strategies for Mycotoxin Detoxification

Nutrient/Compound	Main Mechanism of Action	Target Mycotoxins	Animal Model	Reference(s)
Selenium (Se)	**Antioxidant, regulation of CYP450 enzymes, reduces inflammation and cell damage**	**AFB1, DON**	**Poultry, Piglets**	**[144] , [145]**
Vitamins A, C, E	**Antioxidant, scavenging free radicals**	**AFB1,ZEN, OTA**	**Mice, Poultry**	**[146], [147]**
Vitamin B1 (Thiamine)	**Reduced toxicity of Fusarium toxins**	**Fusarium toxins**	**Poultry**	**[148]**
Vitamin E	**Reversed FB1-induced reproductive and hormonal effects**	**FB1**	**Rabbits**	**[149]**
Carotenoids	**Liver protection, anti-carcinogenic effects**	**AFB1**	**Rats**	**[150]**
Silymarin	**Hepatoprotection, antioxidant activity, gene regulation**	**AFB1, ZEN**	**Rats, Broiler chickens**	**[151], [152]**
Curcumin	**Downregulation of CYP450s, improved antioxidant enzyme activity**	**AFB1,DON, FB1**	**Chickens, Cell cultures**	**[152] , [153]**
Quercetin	**Suppressed AFB1 bioactivation, reduced oxidative stress**	**AFB1**	**Bovine epithelial cells**	**[154]**
Resveratrol	**Increased total antioxidant capacity, improved plasma proteins**	**AFB1**	**Broilers**	**[155]**
Rhamnoides Oil	**Liver protection against aflatoxin exposure**	**AFs**	**Broilers**	**[156]**
Methionine	**Mitigated DON-induced toxicity**	**DON**	**Piglets**	**[157]**
Glutamic Acid, Arginine, etc.	**Improved antioxidant and physiological responses**	**DON**	**Fattening pigs**	**[158]**
Astragalus Extract	**Immunomodulatory and organ protective effects**	**DON**	**Mice**	**[159]**
Soy Isoflavones	**Reduced ZEN-induced reproductive toxicity, anti-inflammatory**	**ZEN, FB1**	**Gilts, Rats**	**[145], [160]**
Essential Oils (e.g., Citral)	**Disruption of cell membrane, inhibition of fungal metabolism and replication**	**Aflatoxins(A. flavus)**	**In vitro**	**[161], [162]**
Citric Acid, Cinnamaldehyde	**Altered cell permeability, inhibited DNA/protein synthesis in fungi**	**Aflatoxins**	**In vitro**	**[163]**

Conclusions

To mitigate these economic and health impacts, practical strategies must be adopted across the agricultural value chain. The following are key recommendations and proposed applications:

For the Agricultural Sector:

1. Implement regular screening programs for fungal contamination at harvest.
2. Promote crop rotation and the use of resistant crop varieties to reduce fungal colonization.
3. Adopt precision irrigation and soil management to avoid moisture buildup.

For the Food and Feed Industry:

1. Use integrated detoxification approaches, combining mycotoxin binders and microbial additives in feed.
2. Invest in post-harvest technologies such as proper drying, sorting, and storage systems.
3. Apply real-time monitoring and quality control tools for mycotoxin detection.

Storage and Transport Guidelines:

1. Maintain humidity levels below 65% and temperatures below 25°C in grain silos.
2. Avoid using damaged containers; ensure proper aeration during transport.
3. Implement first-in, first-out (FIFO) protocols to minimize storage duration.

Public Awareness and Farmer Education:

1. Launch awareness campaigns highlighting the health and economic risks of mycotoxins.
2. Train farmers on best practices in harvesting, drying, and storing crops.
3. Distribute user-friendly guides and mobile applications for toxin risk alerts.

Overall, early detection, integrated management, and effective policy support are essential tools to minimize the economic burden of mycotoxins and ensure the quality and competitiveness of agricultural exports.

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Conflicts of Interest

The authors declare no conflict of interest.

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