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BIOLOGICAL STRATEGIES FOR REDUCING MYCOTOXIN CONTAMINATION IN SOME FOODS AND ANIMAL FEEDS

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ABSTRACT: Mycotoxins pose a persistent threat to food security, animal productivity, and public health, particularly in countries with diverse climates, agricultural intensification, and complex supply chains such as China. The primary purpose of this study is to investigate and critically evaluate effective strategies for mitigating mycotoxin contamination in selected food and animal feed commodities within the agricultural context of China. Mycotoxins are being toxic secondary metabolites produced by fungal genera such as *Aspergillus*, *Fusarium*, and *Penicillium* are pose a significant and persistent threat to food safety, animal health, and public health globally. This is particularly relevant in China, where diverse agroclimatic conditions, rapid industrialization of the livestock sector, and variable post-harvest practices have heightened the risk of contamination. Therefore, the overarching aim of this study is to investigate and evaluate effective biological strategies for reducing mycotoxin contamination in selected foodstuffs and animal feed in China.

Key words: Mycotoxins; Contamination; Fungi; *Aspergillus;* foods; animal feeds; China.

INTRODUCTION

Mycotoxins are secondary toxic metabolites produced by various filamentous fungi, primarily species of *Aspergillus*, *Fusarium*, and *Penicillium*. These toxins pose significant threats to food and feed safety worldwide due to their harmful effects on both animal and human health. In China, the occurrence of mycotoxins in agricultural products has drawn increasing concern over the last decade, due to rapid agricultural expansion, diverse climatic conditions, and evolving storage practices. Recent nationwide surveillance has demonstrated the widespread contamination of animal feeds and raw materials with multiple mycotoxins in China.

Conducted a five-year investigation covering 9,392 samples collected from various regions between 2017 and 2021. Their study found that more than 75% of samples were contaminated with at least one type of mycotoxin, with *Fusarium* toxins especially fumonisins and deoxynivalenol being the most frequently detected. Aflatoxins and zearalenone were also prominent, particularly in warmer and humid provinces such as Jiangsu and Anhui. The co-occurrence of multiple mycotoxins was common, which increases toxicological risks due to possible synergistic effects. **Li et al. (2022)** further examined 1,610 samples of commercial feed and feed ingredients collected across China in 2020. Their findings highlighted a high frequency of trichothecenes B (72%), zearalenone (47%), fumonisins (63%), and aflatoxins (16%). This data demonstrates that despite regulatory interventions, mycotoxin contamination remains a persistent issue across various regions and feed types **.** The toxicological effects of mycotoxins on animals include hepatotoxicity, immunosuppression, neurotoxicity, and impaired reproductive functions. These outcomes not only reduce animal productivity and welfare but also threaten food safety via toxin residues in meat,

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milk, and eggs. In severe cases, mycotoxins can lead to livestock mortality. Human exposure, particularly to aflatoxins and ochratoxins, is associated with chronic diseases, including liver cancer and nephropathy. **Ma et al. (2018)** observed that livestock feeds often contain multiple mycotoxins simultaneously. These combinations can compound the effects of individual toxins, making management and detoxification particularly challenging. For instance, fumonisins and deoxynivalenol are frequently detected together in maize-based feed ingredients, causing intestinal and immune dysfunction in pigs and poultry. Detection of mycotoxins in feed materials in China has advanced through the adoption of sensitive analytical techniques, such as liquid chromatography–mass spectrometry (LC-MS/MS). The studies by **Li (2023)** utilized standardized sampling and testing protocols to ensure reliable data. However, the diversity of feed types and regional agricultural practices complicates risk assessments. Routine surveillance is often limited by cost, especially among small- and medium-scale farms. Moreover, inconsistent testing frequency and limited capacity for advanced laboratory analyses in rural regions hinder rapid identification of contaminated batches. These challenges call for enhanced investment in rapid testing technologies and capacity-building for on-site screening.

China has established national maximum permissible levels for several major mycotoxins, such as aflatoxin B1, zearalenone, fumonisins, and deoxynivalenol, in both food and feed. For example, the limit for aflatoxin B1 in complete feed for pigs is set at 10 μg/kg. Nevertheless, multiple studies have reported that a substantial portion of feed samples exceed these thresholds, especially in summer months when temperature and humidity conditions are favorable for fungal growth **(Tian, 2022; Zhang, 2023; Liu, 2022).** Enforcement of mycotoxin regulations faces logistical difficulties, especially in decentralized and rural feed production systems. Additionally, awareness among feed producers and farmers about the risks and control strategies remains limited. Several ongoing challenges continue to limit effective mycotoxin control in China. Firstly, climate variability contributes to seasonal and regional shifts in fungal proliferation. Secondly, the lack of widespread adoption of integrated control strategies at the farm level such as timely harvesting, proper storage, and the use of mycotoxin binders exacerbates contamination risks. There is an urgent need for developing and implementing multi-pronged mitigation strategies combining good agricultural practices (GAP), biological control methods, and real-time mycotoxin monitoring. As highlighted by **Ma et al. (2018),** research into bio transforming microorganisms and enzymatic detoxification holds promise but remains underutilized at the commercial scale.

China, as a key player in global agricultural trade, must comply with strict food safety regulations such as those from the **Codex Alimentarius**, **European Food Safety Authority (EFSA)**, and other international bodies. This study contributes to China's ability to meet or exceed these standards by offering practical, evidence-based methods for mycotoxin control, especially in feed and cereals that are often exported.

Overview of Mycotoxins

Mycotoxins are toxic secondary metabolites produced by certain species of fungi, including *Aspergillus*, *Penicillium*, and *Fusarium*. These toxins can contaminate a wide range of agricultural products, posing significant risks to human and animal health. The presence of mycotoxins in food and feed is a global concern, necessitating effective detection and mitigation strategies (**Bertani, et al., 2020**). According to a study by Sun, et al., mycotoxins are widespread contaminants in food and feed, and their occurrence in cereals, nuts, and grains has become a major concern in global food safety (**Sun, et al., 2023**).

Classification and Types of Mycotoxins

Mycotoxins are classified based on their chemical structure and the fungal species responsible for their production. The most commonly encountered mycotoxins are listed in **Table 1** and include:

Aflatoxins: Are potent carcinogenic mycotoxins produced by Aspergillus species, particularly A. flavus and A. parasiticus. Among them, Aflatoxin B1 (AFB1) is a major risk factor for liver cancer. A study by (**Ahmad, 2023**) provides a comprehensive overview of the occurrence, regulations, prevention, and control methods of aflatoxins in peanuts and maize, highlighting their significant health risks.

Ochratoxins: Ochratoxins particularly ochratoxin A (OTA), are mycotoxins commonly produced by Aspergillus and Penicillium species. In their 2022 review, Ran Xu et al. discussed the significant impact of OTA on animal health and productivity in food animal production systems. OTA is frequently found in contaminated cereals such as wheat and maize, posing risks to kidney and liver function in animals. The authors highlighted that chronic exposure, even at low levels, can impair growth performance and immune function without overt clinical signs. Moreover, when OTA co-occurs with other mycotoxins, synergistic or additive toxic effects may arise, further compromising animal health. Xu et al. also emphasized the importance of implementing integrated mitigation strategies, including proper feed storage, mycotoxin binders, and advanced monitoring techniques to reduce OTA exposure in animal feeds (**Ran Xu, 2022**).

***Fusarium* Toxins**: **Ji et al. (2019**) conducted a comprehensive review addressing the occurrence, toxicity, biosynthesis, and detection of *Fusarium* mycotoxins, highlighting their significance in global food and feed safety. The authors focused on the major classes of *Fusarium*-derived toxins, including **trichothecenes** (such as deoxynivalenol, T-2 toxin, and HT-2 toxin), **fumonisins** (notably fumonisin B1), and **zearalenone**. Their review emphasized the widespread contamination of cereal crops like maize, wheat, and barley, especially under favorable environmental conditions that promote fungal growth. Ji and colleagues outlined the diverse toxicological effects associated with these compounds, such as immunosuppression, reproductive dysfunction, and carcinogenicity, affecting both humans and livestock. Importantly, the authors underscored the chemical stability of these toxins, which allows them to persist through food processing, thereby increasing the risk of chronic dietary exposure. The review also provided an overview of current analytical approaches for the detection of *Fusarium* toxins, and called for improved monitoring, regulatory frameworks, and integrated management strategies to reduce their impact on food safety (**Ji et al., 2019**).

Trichothecenes: In his comprehensive review, provides an extensive examination of mycotoxins in food, with a particular focus on the occurrence, health implications, and control strategies of these toxic compounds. Among the key mycotoxins discussed, **trichothecenes** are highlighted as one of the most significant groups produced by *Fusarium* species (Figure 1), particularly *Fusarium graminearum*, *Fusarium culmorum*, and *Fusarium verticillioides*. Trichothecenes include mycotoxins such as **deoxynivalenol (DON)**, **T-2 toxin**, and **HT-2 toxin**, which are commonly found in cereal crops, including wheat, barley, and maize of

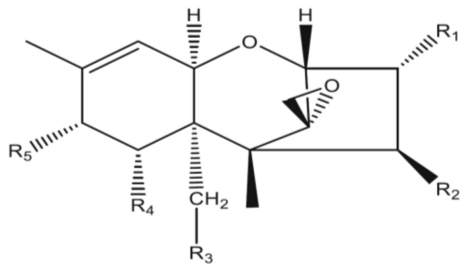

Figure1 Structures trichothecenes

Khan's review emphasizes the severe toxicological effects of trichothecenes, which primarily exert their harmful impacts by inhibiting protein synthesis within cells. This inhibition leads to a broad spectrum of adverse effects, including immunosuppression, gastrointestinal damage, hematotoxicity, and reduced productivity in livestock. Specifically, **DON** is known for its emetic effects, leading to vomiting in animals, while **T-2 toxin** and **HT-2 toxin** cause more severe toxicity, including cell death, hemorrhage, and immunosuppression.

The also underscores the chemical stability of trichothecenes, which contributes to their persistence in food and feed even after processing. This stability poses a significant challenge for food safety management. To mitigate the risks associated with trichothecenes, advocates for a multi-faceted approach, which includes the implementation of good agricultural practices, proper storage conditions, and effective detection methods. Furthermore, the review highlights the importance of regulatory measures and surveillance to ensure consumer safety and reduce the potential health risks of trichothecene exposure.

Pandey et al. (2023) provide a comprehensive classification of mycotoxins based on their fungal origin, chemical structure, and toxicological relevance in food and feed chains. These toxins are primarily synthesized by species of the genera *Aspergillus*, *Fusarium*, and *Penicillium*, which thrive under specific climatic and environmental conditions, leading to widespread global contamination of cereals, nuts, spices, dried fruits, and other stored foods.

The authors classify mycotoxins into five major groups of concern due to their prevalence and severity of toxicity: **aflatoxins**, **ochratoxins**, **trichothecenes**, **zearalenone**, and **fumonisins**. Among these, **aflatoxins** especially aflatoxin B_1 (AFB_1) are the most studied due to their hepatocarcinogenicity and frequent detection in maize, peanuts, and tree nuts. They are produced mainly by *Aspergillus flavus* and *A. parasiticus*, particularly in warm, humid environments **(Figure 2).** AFB_1 is classified as a Group 1 human carcinogen by the International Agency for Research on Cancer (IARC) (**Pandey et al., 2023**).

Ochratoxin A (OTA), produced by *Aspergillus ochraceus* and *Penicillium verrucosum*, is nephrotoxic and immunosuppressive, commonly found in stored cereals, coffee, and dried fruits. **Trichothecenes**, a large group of sesquiterpenoid toxins produced by *Fusarium* spp., include type A toxins (e.g., T-2 toxin, HT-2 toxin) and type B toxins (e.g., deoxynivalenol, or DON). These compounds inhibit protein synthesis, impair intestinal function, and cause anorexia and emesis in monogastric animals (**Pandey et al., 2023**).

Zearalenone (ZEN), another metabolite of *Fusarium graminearum* and *F. culmorum*, mimics estrogen and disrupts reproductive function, particularly in swine. **Fumonisins**, produced by *F. verticillioides* and *F. proliferatum*, interfere with sphingolipid metabolism and are associated with porcine pulmonary edema and leukoencephalomalacia in horses (**Pandey et al., 2023**).

Pandey et al. further acknowledge several emerging mycotoxins such as enniatins, beauvericin, and moniliformin that are increasingly detected using advanced chromatographic and mass spectrometric methods, although their toxicological significance is still under investigation. This evolving spectrum of fungal toxins highlights the complexity of mycotoxin monitoring and risk assessment, necessitating multi-target detection approaches and region-specific surveillance programs **(Pandey et al., 2023**).

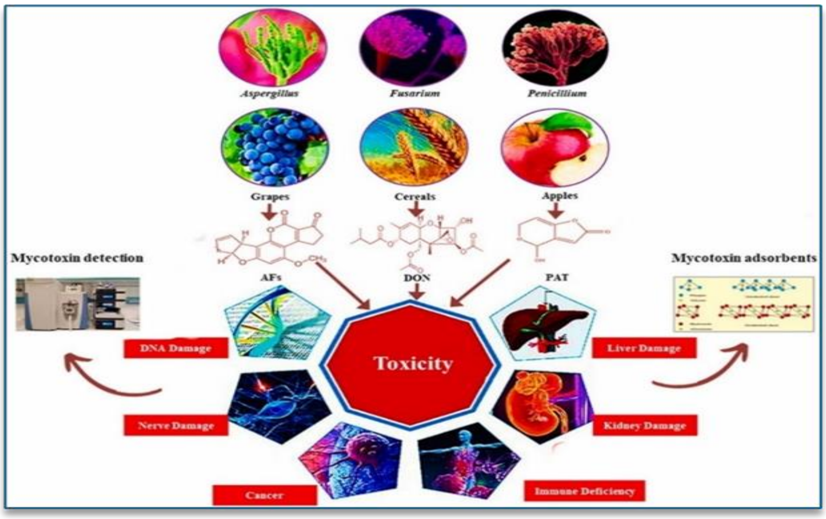

Figure *2* Mycotoxins in food: Occurrence, health implications, and control strategies-A **(Khan, 2024)**

Table 1 List of important mycotoxins, most prone food commodities to be contaminated by mycotoxins and their principal toxic effects.

Mycotoxins	**Related molds**	**Most prone food products to be contaminated**	**Symptoms/toxicology**
Aflatoxins	*Aspergillus parasiticus*, *A. nomius*, and *A. flavus*	Grain, cherries, strawberries, groundnut, raspberries, maize, peanuts, maize, cotton, pearl millet, sorghum, pistachios, chillies, cassava, oil seeds, spices, and dried fruits	Depressed immune response, liver tumours, Liver necrosis, reduced growth, carcinogenic, hepatotoxic, mutagenic, teratogenic, vomiting, and pulmonary convulsions
Cyclopiazonic acid	*A. flavus*, *A. oryzae*, *A. versicolor*, *A. tamarii*. *P. patulum*, *P. verrucosum*, *P. camembertii*, *P. cyclopium*, *Penicillium griseofulvum*, and *P. puberulum*	Peanuts, maize, cheese etc.	Neurotoxin, cytotoxicity, weight loss, immunotoxicity, diarrhea, muscle, nausea, viscera necrosis, and convulsions
Deoxynivalenol, Vomitoxin, Zearalenone	*Fusarium graminearum* and *F. subglutinans*	Wheat, maize, oats, maize, rice, sorghum, and barley	Diarrhoea, vomiting, decreased weight gain, feed refusal, infertility, hepatotoxic, genotoxic, immune-toxic, hemato-toxic, and oestrogenic effect
Fumonisin B1 and Fumonisin B2	*F. moniliforme* and *F. verticillioides*	Maize, rice, and wheat	Porcine pulmonary edema, equine leukoencephalomalacia, kidney disease, liver tumor, hepatotoxic, nephrotoxic, cytotoxic, and oesophagal cancer
Trichothecenes	*F. culmorum*, *Trichoderma*, *F. graminearum*, *F. poae*, *Cephalosporium*, and *Trichothecium*	Wheat, oats, and maize	Food toxic aleukia, necrosis, oral lesion in broiler chickens, weight loss, vomiting, diarrhoea haemorrhages, growth retardation, cartilage tissue damage, fever, dizziness, fever, and neurotoxic.
Ochratoxin	*A. ochraceus*, *P. verrucosum*, and *A. carbonarius*	Wheat, spices, grapes, and coffee	Various poultry symptoms; porcine nephropathy, genotoxicity, immunotoxicity, embryotoxicity teratogenicity, neurotoxicity, protein, RNA, and DNA synthesis inhibitor

Patulin and Citrinin	*P. expansum*	Apple, orange, grapes, and related products	Kidney damage, nephrotoxic, immunotoxicity, teratogenic, hepatotoxic, and foetotoxic
Sterigmatocystin	*A. parasiticus, A. versicolor, A. flavus, A. nidulans, A. rugulosus, A. rubber, A. chevalieri, P. camembertii, A. amsyelodami, P. griseofulvum, P. communer*	Maize, rice, wheat, and hay	Carcinogenic, mutagenic, immunotoxicity, cytotoxicity, diarrhea, nausea, and weight loss.
Alternaria toxins: alternariol, tenuazonic acid and others	*Alternaria* species	Grains, oil seeds, spices, and various fruits and vegetables	Cytotoxic, genotoxic, teratogenic, mutagenic, fetotoxic, and dermal toxicity

Mechanisms of Toxicity

Mycotoxins exert their toxic effects through various mechanisms: For example **Aflatoxins:** Aflatoxins, and particularly aflatoxin B1 (AFB_1), represent one of the most hazardous groups of naturally occurring mycotoxins due to their high toxicity and proven carcinogenicity. They are primarily produced by Aspergillus flavus and Aspergillus parasiticus, and are commonly found in staple crops such as maize, ground nuts, and cottonseed. In their investigation, **Lizárraga-Paulín et al. (2011)** examined the toxicological profile of aflatoxins and emphasized the metabolic activation of AFB_1 in the liver, which leads to the formation of reactive intermediates capable of binding to DNA, resulting in mutagenic changes. This mechanism underlies the classification of AFB_1 as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC). The authors also highlighted the widespread impact of chronic exposure to AFB_1, particularly in developing regions, where regulatory control may be insufficient to prevent contamination and protect public health. Based on the comprehensive review by Mahato et al., Aflatoxins, particularly aflatoxin B_1 (AFB_1), are widely recognized for their potent carcinogenic properties. These mycotoxins are classified as Group 1 carcinogens by the International Agency for Research on Cancer (IARC) due to their clear association with liver cancer. AFB_1 is primarily produced by Aspergillus species, notably A. flavus and A. parasiticus, and is commonly found in contaminated agricultural products such as maize and peanuts. According to Mahato et al., the carcinogenicity of AFB_1 is attributed to its ability to undergo metabolic activation in the liver, where it forms a highly reactive intermediate. This reactive form binds to cellular DNA, causing mutations that contribute to the development of hepatocellular carcinoma. The review underscores the global prevalence of aflatoxins and their significant public health risks, particularly in regions with inadequate food safety regulations. It highlights the need for continuous surveillance, effective detection methods, and comprehensive regulatory measures to reduce AFB_1 contamination in the food supply chain **(Mahato et al., 2019).**

Biological Methods for reducing mycotoxins

Pandey et al. (2023) highlight the increasing relevance of biological methods as sustainable and environmentally friendly approaches for mycotoxin decontamination in food and feed. Unlike physical and chemical methods, biological strategies aim to **biotransform or bind** mycotoxins using specific microorganisms or enzymes, often without compromising nutritional or sensory qualities. The authors emphasize that biological degradation can occur through microbial metabolism or enzymatic catalysis, with the potential for selective and irreversible detoxification. The review identifies several **bacterial genera**, including *Bacillus*, *Lactobacillus*, and *Pseudomonas*, that exhibit capacity to degrade aflatoxins, fumonisins, and deoxynivalenol (DON). For instance, certain *Bacillus subtilis* strains produce carboxypeptidases and esterases capable of cleaving the lactone or epoxide rings of aflatoxins and trichothecenes, reducing their toxicity. Similarly, *Lactobacillus rhamnosus* strains have been shown to bind aflatoxins via cell wall components (e.g., peptidoglycans), thus limiting their absorption in the gastrointestinal tract when used as feed additives **(Pandey et al., 2023).** Fungal organisms also show promise. *Trichoderma* spp., for example, are known to produce extracellular enzymes that degrade zearalenone (ZEN) into non-estrogenic metabolites. Additionally, *Aspergillus niger* has demonstrated capacity to reduce fumonisin B_1 through enzymatic hydrolysis of its tricarballylic acid side chains. Pandey et al. further discuss **yeast-based detoxification**, where *Saccharomyces cerevisiae* binds mycotoxins via its β-D-glucan-rich cell walls a mechanism used in commercial feed supplements also, Enzyme-based methods are another focal point. Enzymes such as **aflatoxin oxidase**, **fumonisin esterase**, and **epoxide hydrolase** have been isolated and characterized for their specificity and catalytic efficiency. These enzymes, derived from microbial or recombinant systems, offer targeted degradation under mild conditions. However, their scalability and cost-effectiveness remain under evaluation **(Pandey et al., 2023).**

Use of Microorganisms for Detoxification

In their detailed review, **Ansari and Rezaei (2022)** provide a comprehensive examination of microbial mechanisms involved in the biological detoxification of mycotoxins, emphasizing the growing importance of such approaches as alternatives to conventional physical and chemical treatments. The authors outline three core microbial strategies for mycotoxin detoxification: surface binding, enzymatic degradation, and metabolic transformation. The first mechanism surface binding is primarily facilitated by the structural components of microbial cell walls. For instance, the cell walls of *Saccharomyces cerevisiae* are rich in β-glucans and mannan oligosaccharides, which have demonstrated strong adsorptive capacity for toxins such as aflatoxin B1 (AFB1), ochratoxin A (OTA), and zearalenone (ZEN). Ansari and Rezaei cite studies in which these yeast cell wall components formed non-covalent, reversible complexes with mycotoxins, limiting their bioavailability in the gastrointestinal tract and preventing systemic toxicity. Notably, they report that esterified glucomannan—a derivative of the yeast cell wall—could bind substantial amounts of multiple toxins through hydrophobic and hydrogen bonding interactions. To explores detoxification through **enzymatic degradation**, where microorganisms secrete enzymes that catalyze the structural breakdown of toxins. Enzymes such as laccases and esterases, produced by *Bacillus subtilis*, *Cladosporium uredinicola*, and *Aspergillus niger*, have been shown to degrade AFB1 into less toxic metabolites. Also, highlight specific degradation pathways, such as the oxidative transformation of the lactone ring in AFB1 and the enzymatic cleavage of the ketone functional group in deoxynivalenol (DON). These biochemical reactions reduce toxicity without generating harmful by-products, making enzymatic detoxification a safe and efficient method for application in food and feed systems. A third mechanism addressed by the authors is **microbial metabolic transformation**, where living microbial cells convert mycotoxins into less toxic or inactive forms through metabolic pathways. For example, species like *Pseudomonas putida* and *Rhizopus oryzae* have been found to metabolize AFB1 into AFD1, AFD2, and aflatoxicol B compounds with significantly lower toxicity. However, Ansari and Rezaei caution that while the initial products of metabolism may appear less harmful, their safety profiles must be rigorously validated to confirm the absence of latent toxic effects. Crucially, the review underscores that the **efficacy of microbial detoxification is strain-specific** and influenced by multiple factors such as microbial concentration, viability, environmental pH, and exposure duration. For example, heat- or acid-treated microbial cells were observed to enhance toxin binding capacity, likely due to increased availability of binding sites resulting from protein denaturation. The authors conclude that microbial detoxification methods, especially those employing probiotic strains, offer a promising, low-cost, and eco-friendly alternative for mitigating the risk of mycotoxin contamination in agricultural commodities. The use of probiotic lactic acid bacteria (LAB) for the detoxification of mycotoxins has emerged as a promising biological approach, owing to the safety, efficiency, and adaptability of these microorganisms in food systems. In a comprehensive review, **Piotrowska (2021)** critically examined the potential of LAB strains in the microbiological decontamination of major mycotoxins such as aflatoxin B1 (AFB1), ochratoxin A (OTA), and zearalenone (ZEN). The author underscored the significance of LAB's probiotic nature, which makes them particularly suitable for application in the gastrointestinal environment where mycotoxin exposure can be effectively mitigated. According to the study, the primary mechanism employed by LAB in detoxifying mycotoxins is surface binding, wherein toxins adhere to components of the bacterial cell wall, including peptidoglycans, teichoic acids, and polysaccharides. These interactions, although non-covalent and reversible, significantly reduce the bioavailability of toxins, thereby limiting their absorption and toxicological impact. On ther other hand he observed that highlighted that several strains of LAB, including *Lactobacillus rhamnosus*, *L. plantarum*, and *L. casei*, have demonstrated notable efficacy in binding mycotoxins in vitro and in vivo. For instance, *L. rhamnosus* GG and LC-705 strains were reported to effectively bind AFB1 and OTA, achieving binding efficiencies as high as 80–90% under optimized conditions. Additionally, the review presented evidence that the toxin removal capacity of LAB is highly strain-specific, influenced by cell surface composition, viability, and environmental factors such as pH and temperature. This specificity underscores the importance of targeted strain selection for practical applications in food and feed detoxification. Furthermore, they discuss practical implementation strategies, recommending incorporation rates ranging from 0.2% to 9% in cereal processing to optimize adsorption while preserving nutritional value. Thus, the work of Zhang and colleagues underscores the critical role of cell wall architecture in mycotoxin adsorption and supports the targeted deployment of yeast-derived adsorbents in food and feed safety protocols **(Zhang, 2023).** In their comprehensive review, **Liu et al., (2022a)** explored the biological detoxification of mycotoxins with a particular emphasis on the synergistic potential of microbial consortia and enzyme-mediated degradation pathways. The authors argue that while single microbial strains may exhibit selective activity against specific mycotoxins, **microbial consortia omprising bacteria, yeasts, and filamentous fungi offer broader and more robust detoxification capabilities**. These mixed cultures can utilize complementary metabolic pathways, resulting in enhanced degradation efficiency and broader substrate specificity. For instance, the co-cultivation of *Bacillus subtilis* with *Trichoderma* species has been shown to facilitate the simultaneous degradation of aflatoxins, zearalenone, and ochratoxin A through both oxidative and hydrolytic mechanisms. Liu and Xie emphasize that these consortia can mimic natural microbiomes and are particularly effective under complex environmental conditions, such as those found in stored grains or the gastrointestinal tract. In parallel, the study provides an in-depth overview of **enzymatic degradation strategies**, which involve the biochemical transformation of mycotoxins into non-toxic or less toxic metabolites. A wide range of enzymes, including **laccases, manganese peroxidases, epoxide hydrolases, and carboxypeptidases**, have been identified as key agents in this process. For example, laccases produced by certain white-rot fungi have demonstrated efficacy in cleaving the double bond in the furan ring of aflatoxin B1, a transformation that significantly reduces its toxicity. Liu and Xie also highlight the importance of **epoxide hydrolases** in degrading trichothecenes such as deoxynivalenol (DON), by breaking down the 12,13-epoxide ring responsible for its cytotoxic effects. In addition, they address advances in **genetic and protein engineering**, which have facilitated the development of recombinant enzymes with improved catalytic efficiency, thermal stability, and substrate affinity. Moreover, the authors underline that enzyme-based detoxification systems can be applied not only in situ within food and feed matrices but also in vivo, where microbial probiotics expressing detoxifying enzymes can reduce the absorption of toxins in the gastrointestinal tract. The points to emerging tools in **genome mining, metagenomics, and synthetic biology**, which have accelerated the discovery and optimization of novel detoxification enzymes. These developments are seen as critical steps toward establishing **standardized, safe, and scalable biological detoxification technologies** for use in the agri-food industry. **Liu et al., (2022a)** conclude that integrating microbial consortia with tailored enzymatic systems holds exceptional promise for advancing the biodegradation of multiple mycotoxins under practical and industrial conditions

As illustrated in **Figure** 3, biological detoxification mechanisms involve extracellular polymeric substance (EPS) binding, extracellular enzymatic degradation, and intracellular metabolic transformation. This mechanistic diversity underscores the utility of microbial consortia and engineered enzymatic pathways in mycotoxin detoxification strategies **(Liu et al., 2022a)**. In this respect they observed that, microbial biodegradation of aflatoxin B_1 (AFB_1), deoxynivalenol (DON), zearalenone (ZEN), and fumonisin B_1 (FB_1) relies on the metabolic activity of selected bacterial and fungal strains, which are capable of breaking down toxic moieties into less harmful or non-toxic metabolites. This process is often mediated by extracellular enzymes secreted during microbial growth. In their review, Liu and colleagues described various fungal strains such as Aspergillus niger FS10 and RAF106, which achieved degradation efficiencies of 88.6% to 98.7% for AFB_1. The yeast Saccharomyces cerevisiae ŁOCK 0119 showed a moderate degradation rate of 69% under controlled conditions. Notably, bacterial strains from genera such as Bacillus, Pseudomonas, Escherichia, and Stenotrophomonas demonstrated high detoxification potential, often exceeding 90% degradation of AFB_1 within 24 to 72 hours. For example, Bacillus subtilis strains UTBSP1 and JSW-1 achieved degradation rates of up to 95% and 67%, respectively. As for DON, a variety of soil and gut-isolated bacteria—including Devosia insulae, Eggerthella spp., and a bacterial consortium designated C20—were reported to convert DON into 3-keto-DON or 3-epi-DON, with efficiencies ranging between 74% and 100%. Regarding ZEN, several Bacillus species (e.g., B. subtilis ANSB01G and B. pumilus ES-21) degraded over 80–95% of the toxin across different substrates including moldy corn and complete feed. Similarly, fumonisin degradation was achieved by both bacterial consortia and specific strains such as Bacillus spp. S9–S69, with rates up to 100% in optimized conditions **(Liu et al., 2022b).** These findings underscore the value of microbial detoxification as a feed-safe, target-specific strategy. Liu et al. noted, however, that not all strains are viable under in vivo conditions, and that further studies are needed to assess the stability, enzyme kinetics, and safety profiles of the biodegradation products (**Liu et al., 2022b**). As discussed by **Ogunade et al. (2018).** During the ensiling process, specific microbial inoculants—particularly lactic acid bacteria (LAB)—play a dual role: not only do they improve fermentation quality and aerobic stability, but they also exert a detoxifying effect on a range of mycotoxins either directly via enzymatic degradation or indirectly by suppressing fungal growth.

In addition to antifungal activity, some LAB strains possess enzymatic systems capable of binding or degrading specific mycotoxins. While complete detoxification in vivo remains inconsistent and strain-dependent, in vitro experiments have shown partial degradation of aflatoxins, zearalenone (ZEA), and deoxynivalenol (DON) by selected LAB species. For example, certain strains can convert DON into less toxic metabolites such as de-epoxy DON (DOM-1), especially under anaerobic conditions mimicking the rumen. However, **Ogunade et al. (2018)** caution that the efficacy of detoxification is influenced by multiple factors, including strain specificity, inoculum concentration, and interaction with the native microbiota of the forage**.** They also noted that the beneficial effect of microbial inoculants may be compromised under suboptimal ensiling conditions—such as inadequate packing or oxygen ingress—that allow opportunistic fungi to dominate and override the protective effect of the inoculants. Furthermore, the synergistic use of microbial inoculants with chemical additives or physical exclusion strategies (e.g., oxygen barrier films) is suggested as a more robust solution to limit mycotoxin formation. Overall, microbial inoculation represents a biologically sound and practically applicable strategy for mitigating mycotoxins in silage, although further research is required to optimize strain selection and evaluate in vivo efficacy in animal performance trials.

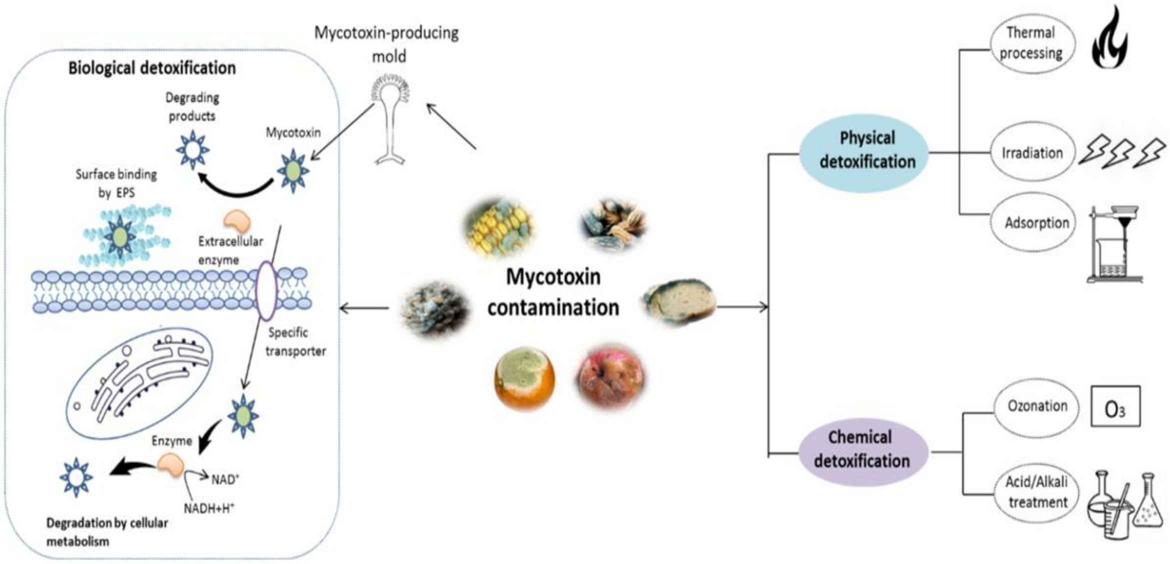

Figure 1 Schematic Representation of Mycotoxin Detoxification Strategies: Physical, Chemical, and Biological Approaches

Reducing contamination by Mycotoxin-Binding Enzymes

An important biotechnological strategy in reducing mycotoxin contamination in animal feed involves the application of mycotoxin-degrading enzymes. Among these, fumonisin esterase (FE) has emerged as a promising candidate for the biotransformation of fumonisin B_1 (FB_1), a prevalent and toxic mycotoxin in maize-based diets. In a pilot study conducted by **Neckermann et al. (2022),** the efficacy of FE was evaluated using piglets as an animal model for human gastrointestinal physiology. The researchers aimed to compare two routes of enzyme administration **intraoral** versus **intragastric** to determine the most effective approach for FB_1 detoxification. The study involved 24 piglets randomly divided into four groups, each subjected to different treatment protocols, including control and FB_1-exposed diets with and without enzyme supplementation. The enzyme used, FUMzyme, is a recombinant fumonisin esterase derived from *Komagataella phaffii*, capable of hydrolyzing FB_1 into hydrolyzed FB_1 (HFB_1), a significantly less toxic derivative. The efficacy of the enzyme was assessed by monitoring biomarkers such as the **sphinganine-to-sphingosine (Sa/So) ratio** in serum and the levels of FB_1 and HFB_1 in urine and feces. Results from the intraoral enzyme group demonstrated a statistically significant reduction in the serum Sa/So ratio, indicating effective detoxification of FB_1 through enzymatic hydrolysis before gastrointestinal absorption. Moreover, high levels of HFB_1 were detected in excreta, further confirming in vivo activity of the enzyme. Comparatively, the intragastric method showed lower detoxification efficacy, suggesting that pre-gastric activation of the enzyme in the oral cavity enhances its performance. Notably, the study demonstrated the feasibility of using piglets as a translational model for assessing enzyme-mediated detoxification in humans. They also noticed that, emphasized that enzymatic treatment offers an efficient and target-specific method for fumonisin mitigation, with potential applications in both animal feed safety and human dietary interventions. Their findings support the integration of fumonisin esterase into feed formulations as a preventative strategy against fumonisin-associated health risks. One of the most scientifically validated approaches to mitigating fumonisin contamination in animal feed involves the use of enzymatic detoxifiers, particularly fumonisin esterases. A comprehensive evaluation of such an enzyme, derived from Komagataella phaffii DSM 32159, was conducted by the EFSA Panel on Additives and Products or Substances used in Animal Feed (FEEDAP) and published in 2018. The study, led by Rychen, et al. (2018), aimed to assess the safety and efficacy of this specific fumonisin esterase as a technological feed additive for pigs and poultry. The enzyme under evaluation functions by hydrolyzing fumonisin B_1 (FB_1) into the much less toxic hydrolyzed form HFB_1 through cleavage of the tricarballylic acid side chains. This mechanism was shown to be highly effective in reducing FB_1 toxicity in feed matrices, especially under gastrointestinal pH and temperature conditions. The panel concluded that a minimum dose of 40 U/kg feed was sufficient for effective detoxification, particularly in silage-based feed formulations. Furthermore, a recommended dose of 60 U/kg was proven to be both efficacious and safe in complete feed for pigs and poultry. Importantly, the safety assessment revealed that the enzyme posed no risk to target species, consumers, or the environment. The production strain K. phaffii DSM 32159 is a non-genetically modified organism, and no viable cells or recombinant DNA were detected in the final product. Additionally, the enzyme showed no signs of dermal or ocular irritation, though it was noted to be a potential respiratory sensitizer due to dust formation. The collective efforts of Rychen et al. provided critical regulatory and scientific justification for the enzyme's use in animal nutrition. In their comprehensive review, **Liu et al. (2022a)** discussed enzymatic detoxification as a promising and biologically precise strategy for mycotoxin mitigation in feed. Unlike traditional adsorbents, enzyme-based systems aim to chemically modify the structure of mycotoxins, thereby rendering them non-toxic or less harmful. These enzymes are typically isolated from microorganisms known for their biodegradation capabilities, including various fungi and bacterial strains. For aflatoxin B1 (AFB1), Liu et al. reported the identification of several key enzymes. Among them, aflatoxin-oxidase, laccase, and manganese peroxidase demonstrated significant degradation potential. Notably, an aflatoxin-detoxifizyme was cloned from Armillariella tabescens, and its recombinant form effectively reduced the mutagenic effects of AFB1. Similarly, Bacillus shackletonii L7 and Myxococcus fulvus were shown to secrete specific enzymes capable of degrading AFB1 through oxidative mechanisms (**Liu et al. 2022b**). In the case of deoxynivalenol (DON), the review detailed the action of aldo-keto reductases (DepA and DepB), which convert DON into less toxic metabolites such as 3-keto-DON and 3-epi-DON. These enzymes were isolated from Devosia strains. Additionally, quinone-dependent dehydrogenases and peroxidases from rice bran and mushroom substrates exhibited significant detoxification effects against DON. Zearalenone (ZEN), known for its estrogenic effects, has been effectively degraded by ZEN-specific lactonohydrolases, including a novel fusion enzyme combining lactonohydrolase and carboxypeptidase genes, which completely inactivated ZEN under physiological conditions. These enzymes were expressed recombinantly using microbial platforms such as Clonostachys rosea and Bacillus amyloliquefaciens (**Liu et al. 2022b**). For fumonisin B1 (FB1), the enzyme fumonisin carboxylesterase (FumD) was highlighted. It hydrolyzes FB1 to non-toxic metabolites in the gastrointestinal tract. Liu et al. demonstrated its effectiveness in ex vivo pig models, where complete degradation of FB1 occurred within two hours in the duodenum and jejunum (**Liu et al. 2022b**). As reported by **Stoev (2024),** certain enzymes derived from microbial sources or genetically modified organisms are capable of **binding**, **modifying**, or **degrading** the molecular structure of mycotoxins, thereby reducing their toxicity and systemic absorption in the host animal. The action of **mycotoxin-modifying enzymes** primarily involves **biotransformation**, in which the toxic parent compound is converted into a less toxic or non-toxic metabolite. This process typically occurs in the gastrointestinal tract following oral administration. For instance, enzymes such as **epoxide hydrolases**, **esterases**, and **oxidoreductases** can target reactive groups within aflatoxins or trichothecenes (e.g., DON), altering their structure and reducing their ability to bind to DNA or cellular proteins. These transformations not only lower the bioavailability of the toxins but also mitigate downstream effects like immunosuppression, hepatotoxicity, and intestinal damage **(Stoev, 2024).** An essential advantage of enzymatic detoxification is its **specificity**: unlike broad-spectrum adsorbents that may also bind nutrients, enzymes act on defined mycotoxin substrates without affecting feed quality or nutrient absorption. However, their effectiveness is influenced by factors such as pH stability, temperature tolerance, and enzyme half-life in the gut environment. Thus, encapsulation techniques and feed formulation adjustments are often necessary to ensure functional activity through the digestive tract **(Stoev, 2024).**

Using Plant and Herbal Additives for reducing mycotoxins in feeds

Aflatoxin B_1 (AFB_1), a potent mycotoxin commonly found in poultry feed, poses significant health risks to livestock, particularly through inducing oxidative stress and hepatotoxicity. In response to this challenge, **Nabi et al. (2022)** conducted a comprehensive investigation to evaluate the protective effects of Penthorum chinense Pursh extract (PCPE), a traditional Chinese herbal medicine rich in antioxidant compounds, against AFB_1-induced liver injury in broilers. The researchers designed a controlled animal experiment in which broiler chickens were fed AFB_1-contaminated diets with or without PCPE supplementation. Through a multidisciplinary approach, they assessed growth performance, liver histopathology, oxidative stress markers, and mitochondrial apoptosis-related pathways. The experimental results revealed that PCPE significantly alleviated liver damage by restoring antioxidant enzyme activity (such as superoxide dismutase and glutathione peroxidase) and by modulating mitochondrial dysfunction. Notably, the extract reduced the expression of pro-apoptotic proteins (e.g., Bax and caspase-9) and increased the levels of anti-apoptotic markers, thereby demonstrating a protective mechanism via mitochondrial pathways. The contribution of the research team was crucial at multiple levels. The increasing occurrence of aflatoxin B_1 (AFB_1) in dairy cattle feed and its hepatic biotransformation into aflatoxin M_1 (AFM_1)—a carcinogenic residue excreted in milk—poses significant risks to public health and dairy product safety. As a response, **Akter et al. (2025)** have explored dietary interventions aimed at limiting mycotoxin bioavailability and enhancing systemic detoxification. Among these, polyphenol-rich agro-industrial by-products such as **grape pomace** have gained attention due to their antioxidative and ruminal-binding properties. Although **Akter et al. (2025)** did not explicitly investigate aflatoxin detoxification, their rigorous evaluation of grape pomace supplementation in lactating Holstein cows provides a valuable foundation for understanding its broader implications on rumen metabolism and systemic health. In their study, published in the *Journal of Dairy Science*, the authors supplemented dairy cow diets with grape pomace and observed a significant reduction in **methane emissions**, alongside notable improvements in **milk fat and protein concentrations**. These physiological responses were largely attributed to the rich content of polyphenolic compounds—such as catechins, anthocyanins, and resveratrol—which modulated rumen fermentation pathways and oxidative balance. Also, The research team, led by Akter and colleagues, implemented a well-structured experimental design involving multiple dietary treatments and metabolic monitoring across lactation stages. Their findings suggest that grape pomace not only functions as a sustainable dietary additive but also exerts biological effects that may intersect with mycotoxin mitigation mechanisms. Specifically, the reduction in methane production implies a shift in microbial activity in the rumen, potentially influencing the binding or degradation of xenobiotics such as AFB_1. Additionally, the observed improvement in milk quality markers supports the hypothesis that grape polyphenols enhance hepatic function and antioxidant status, both of which are critical in limiting AFB, bioconversion to AFM_1 in the liver. Akter et al.'s work, though primarily focused on environmental and nutritional outcomes, underscores the multifunctional value of grape pomace as a feed additive. Their meticulous documentation of biochemical and production responses lays the groundwork for future studies targeting aflatoxin detoxification. As grape pomace is abundantly available from wine and juice industries in both China and abroad, its integration into ruminant diets represents a promising and circular approach to improving food safety in the dairy sector.

Abd El Latif et al. (2023) conducted a comprehensive in vivo experiment to investigate the effects of dietary orange peel meal (OPM), with or without multi-enzyme supplementation, on the performance and physiological responses of broiler chickens. The researchers formulated diets containing 80, 160, and 240 g/kg of OPM and administered them over a 42-day feeding trial. They observed that broilers receiving OPM, particularly in combination with multi-enzymes, showed significant improvements in body weight gain, feed conversion ratio, and crude fiber digestibility. Furthermore, the authors reported enhanced serum triiodothyronine (T_3) levels and improved intestinal histomorphology, including increased villus height, indicating better nutrient absorption. Based on these findings, the study highlights the efficacy of citrus peel by-products as phytogenic feed additives with potential to support gut health and mitigate dietary challenges

Miljanić et al. (2024) investigated the biosorptive properties of blackberry seed cold-pressed oil by-product (BBSOC) as a natural feed additive for the mitigation of aflatoxin B1 (AFB1). Their study demonstrated that BBSOC, characterized by its high content of insoluble fibers (62.09%) and polyphenols such as ellagic acid, exhibited significant adsorption capacity under simulated gastrointestinal pH conditions. In vitro tests at pH 3 and 7 achieved adsorption rates exceeding 85%, indicating strong binding affinity without chemical modification. Surface analysis via SEM and FTIR confirmed the involvement of hydroxyl and carboxyl functional groups in the binding process. These findings support the use of plant-derived by-products as sustainable biosorbents to reduce mycotoxin bioavailability in feed applications, in line with circular economy principles. The use of plant-derived compounds as nutritional and functional additives to mitigate mycotoxin-induced toxicity in livestock has gained significant attention due to their wide-ranging bioactivities**. Xu et al. (2022)** provide a detailed review of phytogenic feed additives, emphasizing their protective roles against the toxic effects of mycotoxins such as aflatoxin B_1 (AFB_1), deoxynivalenol (DON), T-2 toxin, and zearalenone (ZEN). These plant-based compounds exhibit various mechanisms of action, including antioxidant, anti-inflammatory, immunomodulatory, and even direct toxin-binding effects. Among the most studied phytochemicals is curcumin, a polyphenol derived from Curcuma longa, which has demonstrated hepatoprotective effects in poultry and swine exposed to AFB_1 and T-2 toxin. Curcumin exerts its protective role by scavenging reactive oxygen species (ROS), inhibiting lipid peroxidation, and modulating pro-inflammatory cytokines, thereby preserving liver function and improving growth performance. Another key compound discussed by Xu et al. is resveratrol, a stilbene found in grapes and berries, which enhances cellular antioxidant capacity and protects intestinal barrier function in animals challenged with DON or ZEN. **Xu et al. (2022)** further note that plant polyphenols may improve gut health by maintaining tight junction integrity, modulating gut microbiota, and enhancing mucosal immunity, all of which are commonly disrupted by chronic mycotoxin exposure. Additionally, some plant extracts may act synergistically with traditional mycotoxin adsorbents, offering both physical binding and biological recovery. For example, combining curcumin or quercetin with bentonite or yeast-based binders has shown enhanced mitigation efficacy in in vivo trials. Despite these benefits, the authors emphasize that the efficacy of herbal additives is influenced by multiple factors including the specific toxin involved, dosage of the phytochemical, animal species, and the presence of co-contaminants. Therefore, the integration of plant-based additives into feed should be guided by thorough feed testing and scientific formulation strategies. **Stoev (2024)** emphasizes the growing scientific and practical interest in using plant-derived feed additives as an alternative to chemical agents in controlling foodborne mycotoxicoses. These phytogenic substances—such as curcumin, thymoquinone, allicin, and silymarin demonstrate potent antioxidant, anti-inflammatory, and detoxifying properties that can alleviate the adverse effects of various mycotoxins in livestock systems. According to the review, curcumin, extracted from Curcuma longa, enhances hepatic antioxidant capacity and modulates detoxification enzymes via the Nrf2 signaling pathway, thereby reducing oxidative stress and cellular injury caused by aflatoxins and ochratoxins. Similarly, thymoquinone, a component of Nigella sativa oil, exhibits immunoprotective and anti-inflammatory activities that help restore immune balance in animals exposed to trichothecenes like DON. Allicin, derived from garlic (*Allium sativum*), has been shown to interfere with aflatoxin bioactivation by hepatic cytochrome P450 enzymes, lowering the burden of toxic metabolites. Meanwhile, silymarin, obtained from Silybum marianum (milk thistle), stabilizes liver cell membranes and supports hepatocyte regeneration, making it effective against fumonisin-induced hepatic damage. Also, these herbal compounds not only counteract the biochemical effects of mycotoxins, but also improve feed intake, weight gain, immune status, and overall resilience in livestock. Their incorporation into feeding programs offers a multi-target approach that enhances the animal's own defense systems while reducing reliance on synthetic detoxifiers.

Nutritional Approaches to Mitigate Mycotoxin Effects

Liu et al. (2022a) emphasized that nutritional regulation is a complementary and increasingly vital approach for mitigating the subclinical effects of mycotoxins in livestock, particularly when complete detoxification by physical, chemical, or biological means is unattainable. The authors noted that even low levels of mycotoxins such as AFB1, DON, ZEN, and FB1 can lead to chronic toxicity, immunosuppression, and performance decline in animals. Therefore, dietary interventions that enhance endogenous detoxification pathways and counteract oxidative stress are gaining prominence. Key antioxidant micronutrients including selenium, vitamins C and E, retinol (vitamin A), and carotenoids were highlighted for their ability to scavenge reactive oxygen species (ROS) and enhance redox balance in tissues affected by mycotoxins. Selenium supplementation, for example, was shown to protect chicks from AFB1-induced hepatotoxicity and immunotoxicity by modulating selenoprotein gene expression and suppressing pro-apoptotic pathways. Similarly, vitamin E counteracted the reproductive toxicity induced by FB1 in rabbits and improved milk production performance **(Liu et al., 2022b).** In addition to vitamins and trace elements, Liu et al. described the protective roles of natural bioactives such as silymarin, curcumin, quercetin, and resveratrol. Silymarin demonstrated hepatoprotective activity against AFB1 and ZEN, while curcumin modulated cytochrome P450 activity and alleviated DON-induced oxidative damage. Notably, these compounds not only neutralized ROS but also upregulated detoxification-related enzymes such as glutathione S-transferase. Functional amino acids (e.g., methionine, glutamic acid, lysine, arginine) were also mentioned for their role in maintaining immune competence and intestinal integrity in piglets exposed to DON. Moreover, antimicrobial peptides and herbal additives like astragalus and soybean isoflavones were reported to reduce ZEN and FB1 toxicity through endocrine modulation and immune enhancement **(Liu et al., 2022b).** Thus, Liu et al. advocated that dietary fortification with specific micronutrients and phytochemicals represents a cost-effective and biologically relevant mitigation strategy, particularly suited for integrated feed management systems in regions with recurrent mycotoxin exposure. **Ogunade et al. (2018)** emphasized that although ruminants possess a unique microbiota in the rumen capable of degrading some mycotoxins, such as deoxynivalenol (DON) and zearalenone (ZEA), this natural capacity can be overwhelmed by high levels of contamination or compromised by poor nutritional status. Thus, well-designed dietary interventions are essential not only to limit toxin absorption but also to enhance the resilience and detoxification capacity of the animal. One approach highlighted by the authors involves optimizing the fiber and energy balance of the diet. Diets rich in fermentable fiber promote the proliferation of fibrolytic bacteria that contribute to ruminal stability and may facilitate mycotoxin biotransformation. In contrast, high-starch, grain-rich diets can reduce ruminal pH, impair microbial detoxification activity and increase the bioavailability of mycotoxins. This is particularly relevant for toxins like ochratoxin A, which are more resistant to degradation under acidic conditions. Maintaining ruminal pH between 6.2 and 6.8 is therefore crucial for sustaining microbial detoxification activity. Furthermore, the inclusion of specific feed additives with nutritional or protective roles such as organic acids, vitamins, yeast cell wall components, and trace minerals has shown promise. Although not the main focus of the paper. referenced previous studies where antioxidant nutrients like vitamin E and selenium improved immune response and liver function in animals exposed to aflatoxins and trichothecenes. These nutrients help counteract the oxidative stress and cellular damage triggered by mycotoxins (**Ogunade et al., 2018**). Another key recommendation is maintaining protein quality and digestibility, since some mycotoxins (e.g., T-2 toxin and DON) impair rumen microbial protein synthesis and reduce amino acid absorption in the small intestine. By providing highly digestible protein sources, the adverse effects on nitrogen metabolism can be mitigated (**Ogunade et al., 2018**). Ultimately, **Ogunade et al. (2018)** stress that nutritional mitigation must be integrated with other strategies such as ensiling hygiene and the use of microbial inoculants. The diet alone cannot neutralize high toxin loads, but it can significantly reduce the biological impact on animal health and productivity when contamination levels are moderate or subclinical. Thus, tailored rations**—**based on feed testing and toxin profiling**—**should be central to mycotoxin control programs on farms. **Xu et al. (2022)** highlight that beyond detoxification via binding agents, nutritional modulation can significantly reduce the severity of mycotoxicosis by enhancing the animal's physiological resilience, immune competence, and antioxidative defense systems. These strategies aim not to remove the toxins per se, but rather to reduce their bioavailability and biological impact within the host. One core approach is the inclusion of dietary antioxidants such as selenium, vitamin E, and plant-derived polyphenols. They also, report that oxidative stress is a common pathophysiological consequence of exposure to mycotoxins like aflatoxin B_1, DON, and ZEN, leading to cellular damage, lipid peroxidation, and impaired immune function. Antioxidants counteract these effects by neutralizing reactive oxygen species (ROS), stabilizing cell membranes, and supporting hepatic detoxification pathways. For instance, selenium supplementation has been shown to reduce hepatic lesions and improve growth in pigs exposed to DON. Another important aspect involves maintaining optimal nutrient density and digestibility, especially regarding protein and amino acids. Some mycotoxins, particularly trichothecenes, impair intestinal absorption and interfere with protein metabolism. **Xu et al. (2022)** emphasize that providing high-quality protein sources and sufficient energy can help offset nutrient losses induced by intestinal barrier dysfunction and systemic inflammation. Furthermore, supplementing with functional amino acids such as glutamine and arginine may enhance gut integrity and immune responsiveness. they also underscore the role of gut health-supportive additives, including prebiotics, probiotics, and short-chain fatty acids. These compounds not only improve nutrient utilization but also contribute to microbiota stability, which is crucial for modulating immune responses and limiting systemic toxin absorption. For example, butyrate has been observed to restore tight junction integrity in DON-exposed broilers. Ultimately, the authors advocate for a multi-nutrient strategy, whereby feed is formulated not just for growth optimization but also for resilience enhancement under mycotoxin stress. They conclude that integrating these nutritional tactics with other preventive measures, such as good feed hygiene and mycotoxin risk assessment, offers a comprehensive and biologically sound mitigation framework. On the other hand, **Stoev (2024)** emphasizes the crucial role of **nutritional modulation** as a complementary strategy to reduce the toxic effects of mycotoxins in livestock production. While direct detoxification of feed remains essential, enhancing the animal's physiological resilience through **targeted dietary supplementation** has shown promising results in reducing oxidative stress, restoring immune function, and preserving organ integrity in animals exposed to contaminated diets. The author discusses the benefits of **antioxidant micronutrients**, such as **selenium**, **vitamin E**, **zinc**, and **methionine**, in combating the cellular damage induced by mycotoxins like aflatoxin B1 and ochratoxin A.

Selenium, for instance, serves as a cofactor for glutathione peroxidase, an enzyme that neutralizes reactive oxygen species (ROS) generated during mycotoxin-induced oxidative stress. Supplementation with selenium has been shown to improve hepatic antioxidant status and reduce lipid peroxidation in broilers and pigs fed aflatoxin-contaminated feed. **Vitamin E** (α-tocopherol) plays a synergistic role by stabilizing cell membranes and preventing the propagation of oxidative damage. In several animal models cited by Stoev, diets enriched with vitamin E improved immune competence and reduced histopathological liver damage associated with chronic aflatoxicosis. **Zinc**, through its involvement in metallothionein synthesis and enzyme regulation, supports both intestinal integrity and immune responses. Moreover, **methionine** and other methyl donors assist in detoxification by enhancing hepatic function and facilitating the conjugation and excretion of mycotoxins or their metabolites. The author also highlights the importance of **balanced energy and protein intake**, particularly in ruminants, to offset the nutrient losses resulting from mycotoxin-induced anorexia and malabsorption. In poultry, nutritional interventions were associated with improved weight gain, feed conversion ratio, and survival under toxin exposure. The nutritional strategy tailored to the animal species, toxin type, and production system. Such approaches not only mitigate the physiological consequences of mycotoxin exposure but also enhance the efficacy of other control methods such as adsorbents and phytogenic supplements **(Stoev 2024).**

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الاستراتيجيات البيولوجية للحد من تلوث الميكوتوكسين في بعض الاغذية وأعلاف الحيوانات

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تلعب فترات الري دوراً حيوياً في ترشيد مياه الري في المناطق القاحلة وشبه القاحلة. أجريت تجربة حقلية بمحطة الميكوتوكسينات تشكل تهديداً مستمراً للأمن الغذائي، وإنتاجية الحيوانات، والصحة العامة، خاصة في الدول ذات المناخات المتنوعة، وفي ظل النمو الزراعي المتزايد، وسلاسل الإمداد المعقدة في دول مثل الصين. كان الغرض الأساسي من هذه الدراسة هو التحقيق وتقييم الاستراتيجيات البيولوجية الفعالة للحد من تلوث الميكوتوكسينات في بعض الاغذية والاعلاف الحيوانية في الصين.

الميكوتوكسينات هي مركبات ثانوية سامة تُنتَج بواسطة أجناس الفطريات مثل *Aspergillus* و *Fusarium* و *Penicillium* وتشكل تهديداً كبيراً ومستمراً لسلامة الغذاء وصحة الحيوان والصحة العامة على الصعيد العالمي. وهذا ذو صلة خاصة في الصين، حيث الظروف الزراعية-المناخية المتنوعة، وتطور قطاع الثروة الحيوانية بشكل سريع، وتفاوت ممارسات ما بعد الحصاد قد زادت من مخاطر التلوث. لذا، الهدف العام من هذه الدراسة هو التحقيق وتقييم الاستراتيجيات البيولوجية الفعالة للحد من تلوث الميكوتوكسينات في الأغذية والاعلاف الحيوانية في الصين.

الكلمات المفتاحية: الميكوتوكسينات؛ التلوث؛ الفطريات؛*Aspergillus* ؛ الأغذية؛ أعلاف الحيوانات؛ الصين

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