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Advanced Strategies for Mycotoxin Detoxification in Animal Feed: Challenges, Risks, and Innovations

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Abstract

Mycotoxins are toxic secondary metabolites produced by molds, posing a serious threat to livestock health, feed quality, and food security. These harmful compounds originate from environmental stressors and improper feed storage, leading to immune suppression, metabolic disturbances, and reduced productivity in animals. Given their stability and resistance to degradation, mycotoxins persist in feed materials, necessitating effective detoxification strategies to mitigate their risks. Their widespread occurrence across diverse climatic conditions underscores the necessity of global surveillance and intervention measures. Additionally, understanding species-specific sensitivity to different mycotoxins is critical for optimizing protective strategies in livestock. This review examines biological degradation, enzymatic neutralization, and advanced adsorbents, evaluating their efficacy, safety, and cost-effectiveness. Additionally, regulatory frameworks and innovative detection technologies are explored to ensure compliance with global feed safety standards. By synthesizing recent scientific advancements, this study provides a comprehensive perspective on mycotoxin mitigation, offering insights into sustainable livestock management and improved nutritional outcomes. These strategies contribute to enhancing feed security and reducing mycotoxin-related risks, supporting efficient animal production systems worldwide.

1. Introduction

Ensuring food safety remains a fundamental global concern, shaping national and international health policies aimed at hazard prevention. Both microbiological and chemical contaminants impact food security, with mycotoxins-fungal secondary metabolites-recognized by the World Health Organization (WHO) as major contributors to foodborne illnesses (Adelere *et al.*, 2025).

Animal nutrition plays a critical role in maintaining health, optimizing physiological functions, and supporting resilience against environmental stressors. An ideal diet must integrate energy, protein, essential minerals, beneficial microorganisms, and bioactive feed components, all tailored to enhance immunity, digestive efficiency, and reproductive performance (Tegzes, 2025). Livestock feed formulations are strategically designed not only to meet nutritional demands at minimal costs but also to sustain production efficiency, welfare, and overall health (Saghir and Bancroft, 2024).

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2. Chemical Contaminants and Mycotoxins

Chemical contaminants are undesirable substances present in food or animal feed, originating from production processes, environmental exposure, or post-harvest handling. Among these, naturally occurring toxins such as alkaloids and mycotoxins pose significant risks. Mycotoxins are toxins produced by specific molds that grow under warm and humid conditions, affecting a wide range of agricultural commodities, including grains, nuts, dried fruits, coffee beans, and spices (Chain *et al.*, 2024).

Despite the identification of over 300 mycotoxins, aflatoxins, deoxynivalenol (DON), zearalenone, fumonisins, ochratoxins, and T-2 toxin remain the most concerning contaminants in animal feed. These toxins exert neurotoxic, hepatotoxic, carcinogenic, and immunosuppressive effects, leading to nutrient malabsorption, altered gut microbiota, impaired reproduction, and increased disease susceptibility (Santos Pereira *et al.*, 2019, Tegzes, 2025). Chronic exposure further reduces livestock productivity and compromises global food security, contributing to economic losses and sustainability challenges (El-Sayed *et al.*, 2022).

3. Mycotoxin Presence in Animal Feed and Risk Prevention Strategies

The phrase "If feed exists, mycotoxins will exist" reflects the inevitability of fungal contamination in agricultural systems (Santos Pereira *et al.*, 2019, Tegzes, 2025). Molds responsible for mycotoxin production proliferate during feed storage and processing, and even properly dried feed can become susceptible to contamination when environmental conditions favor fungal growth. Proper drying and controlled storage remain among the most effective strategies for preventing mycotoxin formation (Organization, 2023).

4. Mycotoxin Regulation and Control Measures

Given the severity of contamination risks, international regulatory agencies, including the FDA, European Union, and agricultural policy frameworks, enforce strict limits on mycotoxin concentrations in food and feed (Santos Pereira *et al.*, 2019, Yang *et al.*, 2020). However, effective prevention strategies must begin at the source, implementing a comprehensive approach combining:

- Good Agricultural Practices (GAP) to minimize fungal colonization during crop production.
- Good Manufacturing Practices (GMP) & Good Hygiene Practices (GHP) to ensure safe processing and storage and reduce post-harvest contamination.
- Hazard Analysis and Critical Control Points (HACCP) for early identification and mitigation of contamination risks (Fumagalli *et al.*, 2021).
- If mycotoxin contamination occurs, detoxification methods such as:
- Physical strategies (sorting, washing, extraction, heat treatment, irradiation, adsorption),
- Chemical approaches (alkaline treatment, ozone treatment),
- Biological solutions (microbial degradation and enzymatic detoxification) can significantly reduce contamination levels (Liu *et al.*, 2022).

Given regional variations in legal regulations, integrated preventive frameworks, including early warning systems and contamination monitoring, have been established in countries with advanced agricultural sectors, such as the European Union (Table 1)(Fumagalli *et al.*, 2021).

Table 1
Mycotoxin detoxification, regulation, and monitoring approaches

Category	Methods & Strategies
Detoxification	- Physical: Sorting, drying, heat treatment, extraction with solvents - Chemical: Binding agents, alkaline treatment, ozone exposure - Biological: Microbial degradation, enzymatic neutralization
Regulation	- FDA & EFSA mycotoxin limits for livestock feed - National agricultural safety guidelines - Risk assessment and contamination threshold enforcement
Monitoring	- Rapid test kits for mycotoxin detection - Laboratory analysis for toxin quantification - Feed surveillance systems and early warning networks

Table 2
Effects of Mycotoxins on different animals

Animal	Major mycotoxins affecting health	Key health impacts
Sheep	Aflatoxins, Ochratoxins, Zearalenone	Liver toxicity, immunosuppression, reproductive issues, reduced wool quality
Cattle	Aflatoxins, Fumonisins, DON, T-2 toxin	Reduced milk yield, feed inefficiency, liver damage, metabolic disorders
Horses	Fumonisins, Aflatoxins, Ochratoxins	Equine leukoencephalomalacia (ELEM), poor performance, liver toxicity
Dogs	Aflatoxins, Ochratoxins, Penitrem A	Neurological disorders, liver damage, tremors, seizures
Cats	Trichothecenes, Ochratoxins, Citrinin	Kidney dysfunction, digestive distress, hematological disorders

5. Impact of Mycotoxins on Sheep Health

Mycotoxins pose significant health risks to sheep, affecting their immune system, metabolism, and overall productivity. Among the most concerning mycotoxins, aflatoxins and ochratoxins are known to cause liver toxicity, immunosuppression, and reduced growth rates in sheep (Yang *et al.*, 2020). Chronic exposure to contaminated feed can lead to digestive disorders, impaired wool quality, and increased susceptibility to infections (El-Sayed *et al.*, 2022). Additionally, zearalenone, a mycotoxin with estrogenic properties, may disrupt reproductive functions, affecting fertility and lambing success (Santos Pereira *et al.*, 2019). Economic losses due to mycotoxin contamination include reduced feed efficiency, lower meat and wool yields, and increased veterinary costs (Fumagalli *et al.*, 2021).

6. Impact of Mycotoxins on Cattle Health

Mycotoxins significantly affect cattle health and productivity, leading to digestive disorders, immune suppression, and reduced milk yield. Aflatoxins, one of the most toxic mycotoxins, are known to cause liver damage, impaired feed efficiency, and carcinogenic effects in cattle (Elgioushy *et al.*, 2020). Chronic exposure to ochratoxins and fumonisins can result in neurological dysfunction, reproductive issues, and metabolic disturbances (Awuchi *et al.*, 2022). Additionally, deoxynivalenol (DON) and T-2 toxins contribute to reduced appetite, weight loss, and increased susceptibility to infections (Duringer *et al.*, 2020).

Economic losses due to mycotoxin contamination in cattle include lower milk production, poor feed conversion rates, and increased veterinary costs. Regulatory agencies, such as the FDA and EFSA, have established strict limits on aflatoxin levels in dairy feed, as residues can transfer into milk, posing risks to human health (Table 2)(Jiang *et al.*, 2021).

7. Impact of Mycotoxins on Horse Health

Mycotoxins pose a significant risk to equine health, affecting digestive function, neurological stability, and immune response. Horses are particularly susceptible to fumonisins, which can cause equine leukoencephalomalacia (ELEM)-a fatal neurological disorder characterized by ataxia, paralysis, and brain lesions (Pinton *et al.*, 2019). Aflatoxins and ochratoxinscontribute to liver toxicity, reduced feed intake, and immunosuppression, leading to poor performance and increased disease susceptibility (Liesener *et al.*, 2010). Chronic exposure to zearalenone may disrupt reproductive health, mimicking estrogenic activity and affecting fertility (Table 2) (Dänicke *et al.*, 2021).

8. Impact of Mycotoxins on Dog Health

Dogs are highly sensitive to mycotoxins, particularly aflatoxins, ochratoxins, and penitrem A, which can cause severe liver damage, neurological disorders, and immunosuppression (Kearley *et al.*, 2024). Tremorgenic mycotoxins, commonly found in moldy food and decomposing organic matter, lead to vomiting, seizures, tremors, and respiratory distress (Pet Poison Helpline). Chronic exposure to contaminated pet food has been linked to hepatic failure and increased mortality rates, emphasizing the need for strict feed quality control (Table 2)(Tegzes, 2025).

9. Impact of Mycotoxins on Cat Health

Cats, though less prone to indiscriminate eating than dogs, can still suffer from mycotoxicosis due to contaminated pet food. Trichothecene mycotoxins have been associated with lethargy, inappetence, and hematological disorders, including pancytopenia and thrombocytopenia (Parent-Massin, 2004). Ochratoxins and citrinin are known nephrotoxins, leading to kidney dysfunction and metabolic imbalances (Tegzes, 2025). Additionally, aflatoxins can cause digestive distress, jaundice, and hepatic failure, particularly in cases of prolonged exposure (Table 2)(Aquino and Corrêa, 2011).

10. Discussion

Effective quality control measures for raw ingredients and proper feed storage conditions are essential in minimizing mycotoxin contamination in animal feed. Several strategic interventions reduce the risk of high-dose exposure, ranging from physical decontamination methods (such as screening, drying, heat treatment, and raw material purification) to chemical applications (including acids, alkalis, salts, and oxidizing agents). Additional techniques involve binding agents (either mineral-based or microbial-derived from cell wall components) and biological treatments, such as enzymes or microorganisms capable of degrading toxins. Novel strategies, such as ozone exposure and advanced carbon-based nanoparticles, further enhance detoxification efforts.

Beyond conventional detoxification methods, species-specific impacts of mycotoxins must be considered when designing mitigation strategies. Sheep, for example, are highly susceptible to aflatoxins and ochratoxins, which can lead to iver toxicity, immunosuppression, and reproductive disorders. In cattle, chronic exposure to fumonisins and deoxynivalenol results in reduced milk yield, metabolic disturbances, and feed inefficiency. Horses, particularly sensitive to fumonisins, may develop equine leukoencephalomalacia (ELEM), a fatal neurological disorder. Dogs and cats, as monogastric animals, exhibit severe hepatic and renal dysfunction when exposed to aflatoxins and ochratoxins, with symptoms ranging from vomiting and lethargy to neurological impairment (Duringer *et al.*, 2020, Elgioushy *et al.*, 2020, Tegzes, 2025).

These methods aim to lower mycotoxin intake upon feed consumption, mitigating their harmful effects on livestock compared to untreated feed. However, despite their effectiveness in reducing specific mycotoxin levels, no single approach can entirely eliminate all toxins or provide uniform detoxification under varying contamination levels. The efficiency of these interventions is highly dependent on multiple factors, including mycotoxin structure, toxicity mechanisms, animal species, immune status, feed processing parameters, environmental influences, and cost feasibility. As advancements in feed safety technologies continue, comprehensive mycotoxin control from farm to consumer may become increasingly attainable.

11. Conclusion

Preventing mycotoxin production is the most effective strategy to reduce animal exposure risks. However, post-harvest interventions remain critical, including mycotoxin adsorbents or enzyme-based solutions targeting specific toxins in feed. For efficient monitoring, rapid commercial test kits enable screening of individual or multiple mycotoxins, while advanced laboratory diagnostics provide quantitative analysis of diverse mycotoxin profiles through streamlined workflows.

Integrating a holistic control framework-incorporating Good Agricultural Practices (GAP), Good Manufacturing Practices (GMP), Good Hygiene Practices (GHP), quality assurance protocols, and Hazard Analysis and Critical Control Points (HACCP)-ensures feed security and toxin mitigation across the entire food production chain. Additionally, species-specific monitoring protocols should be implemented, ensuring that high-risk animals, such as dairy cattle and equines, receive targeted screening for mycotoxin exposure. Emerging biotechnological solutions, including genetic resistance breeding and microbiome-based detoxification, offer promising avenues for long-term mitigation.

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