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Techniques for controlling mycotoxin contamination of animal feed products

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1 Introduction: mycotoxin challenges in animal feed products

A properly formulated feed may consist of a well-balanced mix of high-quality ingredients and optimal nutrient balance. Feed accounts for the majority of animal production costs; in the case of poultry, feed expenses can reach as high as 75% of the total costs of production (Olugbenga et al., 2015; Alqaisi et al., 2017). Feed produced globally in 2023 was 1295.42 metric tonnes (Kirkpinar et al., 2025). One of the main components of animal feed is corn, which has an annual global production of about 1 billion metric tons (García-Lara & Serna-Saldivar, 2019). The quality and safety of feed significantly influence animal performance and health. While there have been notable advancements in genetics, management practices, and health products that enhance animal production, the overall performance and economic benefits of animal products can be compromised without proper attention to feed safety.

One of the prominent concerns regarding feed safety is mycotoxin contamination. Mycotoxins are harmful secondary metabolites produced by fungi found in agricultural products. These toxins can be present in cereal

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grains (such as corn, oats, wheat, barley, and rye), oilseeds (like soybeans and peanuts), forages, and by-products (including spent grains and dried distillers' grains with solubles), other feed ingredients, and finished feeds. Mycotoxins compromise the quality and safety of feed, posing health and production challenges for animals that consume contaminated products (Pokoo-Aikins et al., 2024). Some adverse effects of mycotoxins on animal production include reduced feed intake, diminished weight gain, decreased feed efficiency, compromised immunity, reduced fertility, damaged organs, decreased egg, meat, and milk yield, and, in severe cases, mortality. Mycotoxin contamination in animals, particularly poultry, often goes unrecognized, making it difficult to detect and treat. The most commonly tested mycotoxins in animal feed products include aflatoxins (AFs), fumonisins (FUM), deoxynivalenol (DON), zearalenone (ZEN), ochratoxin (OTA), and T-2 toxin. However, testing for emerging mycotoxins is still limited. It is nearly impossible to find animal feed ingredients, especially grains, completely free of mycotoxins. Some of the field or pre-harvest mycotoxins include FUM, DON, ZEN, and T-2 toxin, whereas post-harvest mycotoxins include AFs, OTA, and citrinin (Nada et al., 2022). Mycotoxigenic fungi can thrive wherever temperature, moisture, and humidity conditions are favorable. These fungi can infect crops in the field and during post-harvest storage, processing, and feed mixing.

Pre-harvest mycotoxin issues are often caused by poor agronomic practices, inadequate farm management, adverse weather conditions (such as drought or irregular rain), and changes in the weather and virulent mycotoxigenic fungi. Post-harvest contamination can occur under warm and moist conditions. Mitigation strategies include planting mycotoxigenic pathogen-resistant crop varieties, treating soil, providing irrigation during dry conditions, managing pest infestations, and ensuring proper planting and harvesting times. For post-harvest control, measures such as drying grains to reduce the moisture content to about 12–14% (depending on the length of storage), minimizing heat and humidity, and applying additives to inhibit mycotoxigenic fungi growth can be beneficial. However, the effectiveness of strategies to control mycotoxin contamination in animal feed can be hindered by the variability of contamination at different crop and feed production phases (pre-harvest, post-harvest: storage, processing, and formulation). This makes tracking contamination challenging unless regular and appropriate sampling and testing are conducted. Regular testing or using feed additives to mitigate the effects of toxins on animals should be encouraged. However, some of the challenges with testing are proper sampling to get a true picture of the mycotoxin levels in the samples or avoid uneven distribution and underestimation of the mycotoxins in the samples, the turnaround time of test results for methods such as HPLC, LC-MS/MS is usually longer whereas many of the rapid tests may be faster but best for quick field testing for preliminary information, the cost of testing is often expensive with high equipment and reagents costs, having skilled personnel to test the samples accurately, limited access to testing laboratories, disparity in tolerance levels based on geographical region.

Additionally, some control methods may impact the nutritional value and palatability of the feed, making it difficult for animals to consume it. For example, heat and chemical treatments can generate strong volatiles that alter flavor and feed quality. Some control methods may also be economically unfeasible or impractical on a large scale, complicating their implementation.

A holistic approach is required to manage mycotoxin contamination effectively. This approach aims to mitigate its effects on animal production and enhance overall yield, animal welfare, and the economic stability of farms. The subtle and often unnoticed impact of mycotoxin contamination in feed is particularly concerning, as it impairs performance and can be challenging to detect, ultimately leading to significant economic losses.

1.1 Emerging and masked mycotoxins

Due to current advancements in mycotoxin testing of feed, some lesser-known mycotoxins, generally referred to as emerging and masked mycotoxins, are detected during testing. Among the most concerning are found in Table 1 cereals and feed and are most often secondary metabolites of *Fusarium* and *Alternaria* species. In contrast, masked (or modified) mycotoxins are chemically or biologically modified derivatives of regulated toxins. These conjugated forms are produced mainly through plant detoxification pathways and may escape conventional analytical detection, yet they can be hydrolyzed back to their toxic parent compounds in the gastrointestinal tract, making them toxicologically relevant and a hidden risk in food and feed safety assessments (Berthiller et al., 2013; Fraeyman et al., 2017; Gruber-Dorninger et al., 2019; Rychlik et al., 2014). It has been reported that these lesser-known toxins also significantly contribute to the negative effects of mycotoxins on animal performance and health. Like the co-occurrence of some mycotoxins such as FUM and DON, a similar trend is also being seen with emerging mycotoxins, where there are two or more together or a combination of more commonly prevalent toxins with emerging mycotoxins in a single sample. The challenge with these emerging mycotoxins is that there is currently limited information about their toxicity in several animal species. These findings underscore the need for comprehensive studies to understand the mechanisms of action, altered toxicity profiles, chronic exposure outcomes, and expected co-occurrence patterns, taking into account animal species, geographic, storage conditions, plant stress factors, and grain type. Emerging mycotoxins are currently not regulated, yet they are increasingly detected in agricultural produce.

Table 1 Emerging and masked mycotoxins that contaminate crops and their toxicological effects

Category	Mycotoxin	Producer organism	Main crops affected	Toxicological concern
Emerging	Enniatins (ENNs A, A1, B, B1)	*Fusarium* spp.	Wheat, barley, oats, maize	Ionophoric, cytotoxic
	Beauvericin (BEA)	*Fusarium* spp.	Maize, wheat	Ionophoric, cytotoxic
	Fusaproliferin (FUS)	*F. proliferatum*, *F. subglutinans*	Maize	Cytotoxic
	Alternariol (AOH)	*Alternaria* spp.	Cereals, fruits	Genotoxic
	Alternariol monomethyl ether (AME)	*Alternaria* spp.	Cereals, fruits	Genotoxic
	Tenuazonic acid (TeA)	*Alternaria* spp.	Cereals, fruits	Cytotoxic
	Altertoxins (ATX I-III)	*Alternaria* spp.	Cereals, fruits	Mutagenic
Masked	DON-3-glucoside (DON-3G)	*Fusarium* spp.	Maize, wheat	Hydrolyzed to DON in gut
	15-acetyl-DON (15-ADON)	*Fusarium* spp.	Maize, wheat	Toxic metabolite of DON
	3-acetyl-DON (3-ADON)	*Fusarium* spp.	Maize, wheat	Toxic metabolite of DON
	Zearalenone-14-glucoside (ZEA-14G)	*Fusarium* spp.	Maize, wheat	Estrogenic
	Zearalenone-14-sulfate (ZEA-14S)	*Fusarium* spp.	Maize, wheat	Estrogenic
	α-Zearalenol (α-ZOL)	*Fusarium* spp.	Maize, wheat	Estrogenic
	β-Zearalenol (β-ZOL)	*Fusarium* spp.	Maize, wheat	Estrogenic
	Hydrolyzed fumonisins (HFB1, HFB2)	*Fusarium* spp.	Maize	Nephrotoxic
	N-(carboxymethyl)fumonisin B1	*Fusarium* spp.	Maize	Nephrotoxic
	Ochratoxin α (OTα)	*Aspergillus*, *Penicillium* spp.	Cereals, grapes	Nephrotoxic
	Citrinin glucosides	*Penicillium* spp.	Maize, rice	Nephrotoxic
	Patulin conjugates	*Penicillium* spp.	Apples, pears	Genotoxic

Adopted from de Oliveira et al., 2022; Gruber-Dorninger et al., 2019; Fraeyman et al., 2017; Kamle et al., 2022; Kolawole et al., 2024; Milani, 2013.

2 Pre-harvest interventions to control mycotoxins in feed

2.1 Interventions pre-harvest

Preharvest interventions are essential for ensuring host plants are healthy and protected from pathogens. These strategies aim to reduce host–pathogen interactions, limit pathogen growth and spread, and create environments conducive to healthy plant growth. Understanding the lifecycle of mycotoxigenic fungi and how they interact with host plants under various environmental conditions enables farmers to implement targeted strategies. Key factors include knowing how pathogens overwinter, their proliferation conditions, dispersal methods, and which growth stages plants are most vulnerable to infection and mycotoxin contamination. Effective monitoring and early detection can lead to timely interventions that minimize contamination risks, ultimately enhancing harvest quality, safety, and food supply.

2.1.1 Reducing host vulnerability

This is essential for developing crop varieties exhibiting genetic resistance to mycotoxin-producing fungi. The effectiveness of this resistance is influenced by a range of factors, including plant genetics and environmental conditions (Majumdar et al., 2022). Although various crops display differing resistance levels, it is essential to note that none are completely immune (Nankam & Pataky, 1996; He et al., 2013), and the strengths and weaknesses of the various approaches used in reducing host vulnerabilities are indicated in Table 2. Traditional breeding methods have produced some successes; however, they often necessitate a lengthy and cost-intensive process involving multiple generations of selection (Guo et al., 2017; Henry et al., 2009). Traditional breeding and marker-assisted selection (MAS) are widely used for complex traits like Fusarium head blight resistance, which involve multiple QTLs. MAS enables selection based on genetic markers but still requires multi-generational selection (Steiner et al., 2017).

In contrast, recent advances in genome editing, genetic engineering, and microbiome-based approaches are accelerating the development of resistant cultivars, potentially reducing yield loss and mycotoxin contamination. These methods may include the development of enzymes capable of degrading or reducing mycotoxins, such as AFs and FUM (Gomes et al., 2024; Liu et al., 1998; Schmidt et al., 2021; Schmidt et al., 2023). Some engineered plants are being developed to express enzymes like amidohydrolases or ochratoxinase that degrade mycotoxins in planta or during storage (often >70–90% degradation in lab assays) (Sánchez-Arroyo et al., 2024). Additionally, the microbiome associated with plants can enhance resistance through metabolites that

Table 2 Approaches to reduce host vulnerability

Approach	Method/Tool	Benefits	Limitations
Traditional breeding and MAS	QTL mapping, marker-assisted selection	Well-established; integrates with elite varieties	Slow, multi-year process; incomplete resistance
Genome editing and transgenic tech	CRISPR/Cas9, transgenes like AFP proteins	Precise edits; can drastically reduce mycotoxins (>50 %)	Regulatory barriers; risk of resistance evolution
Microbiome-mediated resistance	Endophytes, rhizosphere engineering, extremophiles	Enhances innate host immunity; eco-friendly	Field variability; development of effective consortia
Combining strategies	Pyramiding genes, microbiome + editing	Durable, multi-layered defense	Requires integrated, multidisciplinary programs

strengthen plant defense. Beneficial endophytes and rhizospheric microbes, including extremophilic fungi and PGPR, induce plant defense pathways or detoxify mycotoxins via microbial metabolites (Trivedi et al., 2020; Liu et al., 2024). Effective breeding programs should target specific pathogens and broaden their scope to address diverse mycotoxigenic fungi, incorporating resistance traits from cultivars and landraces used by producers (Gao et al., 2021; Rose et al., 2019). An important note with regard to host resistance is that once deployed in the field, these technologies can have a limited life span, as mycotoxigenic fungi can evolve countermeasures that allow them to defeat the genetic resistances of host plants. Therefore, deploying multiple resistance genes and rotating trait targets will be invaluable to mitigating the evolution of new virulent strains (Anderson et al., 2010; Gomes et al., 2024; Mierziak & Wojtasik, 2024).

2.1.2 Soil health amendment and management

Cultivating healthy soil is crucial for nurturing strong and resilient plants. Farmers can significantly reduce the risk of mycotoxin contamination in crops by adopting several strategic approaches to improve soil quality. The incorporation of organic matter, such as biochar, compost, and cover crops, has been shown by some studies to be effective in suppressing the growth of mycotoxigenic fungi. For example, biochar amendments can reduce fungal pathogen incidence by more than 80%, while compost and cover crops often lower inoculum potential by 30–70% under field conditions (Bonanomi et al., 2007; Pascale et al., 2020; Iacomino et al., 2022). However, excessive application of organic matter can also increase inoculum potential for certain fungi and disease risk by 20%, necessitating careful management (Bonanomi et al., 2007; Pascale et al., 2020). Maintaining optimal soil pH (6.0–7.0) with lime or gypsum amendments can further reduce the severity of mycotoxigenic fungi that thrive in acidic conditions by about 40–60% (Allmaras et al. 1987, Fang et al., 2012). Regular soil testing, combined with timely amendments, helps in achieving this delicate balance. Agronomic practices such as tillage play a significant role in managing the prevalence of mycotoxigenic fungal species. Tillage is used to manage postharvest crop residues, which often harbor plant pathogens that can overwinter and become inoculum sources in the subsequent season (Jasarevic et al., 2025). While tillage can increase the abundance of specific pathogens and saprophytes, ploughing or deep tillage before seeding can help bury infected crop residues and reduce the survival of mycotoxigenic fungi, thereby minimizing the initial inoculum load in the subsequent crop and reducing the proliferation of mycotoxigenic fungi and ensuring a healthier growing environment (Munkvold, 2003; Schmale & Munkvold, 2009).

2.1.3 Plant nutrient management

This is essential for optimal plant health, requiring a balance of macronutrients (nitrogen, phosphorus, potassium) and micronutrients (zinc, iron, manganese) to strengthen crops against diseases. Proper nutrient ratios help plants develop robust structures and defenses, reducing vulnerability to plant pathogens, including mycotoxin-producing fungal pathogens (López et al., 2023). Additionally, organic amendments enhance soil fertility and root systems, making plants more resilient to environmental stress. Although the application of fertilizer is important, overapplication of nutrients, especially nitrogen and phosphorus, can lead to excessive weed growth and increase competition and disease susceptibility (Wang et al., 2022). Previous studies have shown contrasting results regarding the impact of nitrogen (N) fertilization on mycotoxins such as FUM contamination in maize. However, it is widely recognized that maintaining balanced nitrogen levels is essential to minimize FUM accumulation. Both nitrogen deficiency and excessive nitrogen application can significantly increase FUM levels (Ono et al., 2011; Marroca et al., 2008; Blandino et al., 2008). It is also important to note that healthy-looking plants and grains can still be contaminated by mycotoxins, especially when weather conditions are favorable for mycotoxin contamination or when either biotic or abiotic stress triggers mycotoxin synthesis by the pathogen.

2.2 Optimal irrigation strategies to minimize fungal risks

Plants need sufficient water for healthy growth and to develop effective defense systems. However, natural environmental conditions and/or agronomic farming practices can lead to drought and/or flooding of farmlands. Both drought and flooding can compromise plant health, making them vulnerable to pathogens such as mycotoxigenic fungi. Drought stress during grain filling has been consistently associated with elevated FUM and AFs contamination. For example, maize grown under drought and heat stress in Argentina showed FUM and AFs levels up to 2–3 times higher than under optimal moisture conditions (Zanon et al., 2023). Similarly, U.S. field studies have reported FUM B1 concentrations exceeding 20 mg/kg in drought-stressed maize, far above the FDA advisory level of 5 mg/kg for human food (Munkvold, 2003). Conversely, flooding and waterlogging create anaerobic soil conditions that reduce root oxygenation and favor fungal proliferation. Nielsen et al. (2023) observed that 10–14 days of waterlogging increased Fusarium ear rot incidence by 40–60%, accompanied by higher deoxynivalenol (DON) levels. Abdelmoneim et al. (2024) further demonstrated that prolonged flooding stress increased AFs contamination in maize kernels by up to 70% compared to non-flooded controls. Weather modeling studies also predict that changes in the weather will exacerbate both drought and flooding risks, thereby amplifying the frequency and severity of mycotoxin contamination events in maize (Battilani et al., 2013). Therefore, it is crucial to manage water availability, avoiding both drought and prolonged flooding, to mitigate fungal outbreaks and mycotoxin contamination in maize (Nielsen et al., 2023; Abdelmoneim et al., 2024).

To ensure an adequate water supply, various methods can be employed, including precision drip irrigation, deficit irrigation (DI), and smart scheduling (Table 3). Precision drip irrigation is effective for delivering water directly to the plant's root zone, minimizing prolonged surface wetness that can facilitate fungal spore germination (Frimpong et al., 2023). This method reduces leaf wetness duration, which is vital for limiting pathogen transmission associated with contaminated irrigation water (Abdelmoneim et al., 2024). Additionally,

Table 3 Types of crop irrigation and their benefits

Strategy	Benefit	References
Drip irrigation	Water delivered directly to the root; reduced leaf wetness	Frimpong et al., 2023; Abdelmoneim et al., 2024
Deficit irrigation (DI)	Saves water while avoiding over-irrigation	Fereres & Soriano, 2007
Smart IoT/ML systems	Optimize irrigation based on real-time data	Frimpong et al., 2023; Ali et al., 2025; Abdelmoneim et al., 2025
Morning irrigation timing	Leaves dry faster, reducing fungal risk	Das et al., 2023; Nielsen et al., 2023
Leaf wetness monitoring	Improves disease forecasting	Nguyen et al., 2023; Abdelmoneim et al., 2024

using drip irrigation under plastic mulch has been shown to enhance water productivity and significantly reduce AFs levels in maize production.

Integrating deficit irrigation and smart scheduling facilitates strategic water application during drought-sensitive growth stages, enhancing water use efficiency and preventing excessive soil moisture. DI is significant for stabilizing yields and lowering disease risks by avoiding root zone over-saturation (Fereres & Soriano, 2007; Abdelmoneim et al., 2024). Modern smart irrigation systems utilize soil moisture sensors, leaf-wetness sensor data, and predictive modeling, including IoT solutions and machine-learning controllers, to improve water-use efficiency, effectively prevent pathogen buildup and fungal infection risks (Nguyen et al., 2023; Saikai et al., 2023; Rodríguez-Lira et al., 2024; Ali et al., 2025). These combined strategies underscore the importance of technologically informed irrigation management as a foundation for sustainable crop protection and mycotoxin mitigation.

In contrast, overhead irrigation tends to increase leaf wetness and enhances the splash dispersal of pathogens. The deployment of leaf wetness sensors, particularly biomimetic models that replicate plant surfaces, has become invaluable for accurately measuring the duration of leaf wetness. Such data significantly enhances disease forecasting capabilities, enabling growers to avoid high-risk irrigation periods that could lead to increased pathogen proliferation (Abdelmoneim et al., 2024; Nguyen et al., 2023). By understanding and harnessing these advanced irrigation methods, farmers can improve productivity while minimizing risks of diseases and mycotoxin contamination, ultimately leading to more sustainable agricultural practices.

2.2.1 Crop rotation and planting density

Crop rotation and optimal planting density are strategic, vital agronomic practices that influence soil health, microenvironment and disease risks (Table 4). Planting different crop types in succession can enrich the soil biome and improve overall soil structure. Adjusting planting density and spacing is essential for enhancing air circulation around crops, which can significantly impact humidity levels. Promoting optimal plant arrangement encourages healthier growth and makes it less favorable for mycotoxin-producing fungi to thrive. Long-term diversified crop rotations improve microbial network complexity, reduce pathogen-dominated fungal taxa, and bolster soil structure and nutrient cycling (Dong et al., 2023; Panneerselvam et al., 2023). Thus, crop rotation and optimal planting density can help suppress mycotoxin-producing fungi by altering pathogen inoculum levels and humidity around the host. Thoughtful planning in crop spacing creates an environment conducive to robust plant health and reduced disease incidence (Wang et al., 2022).

Table 4 Rotation and density strategies to reduce fungal risks

Practice Area	Strategy	Effect on Microclimate and Soil	Impact on Fungus/Mycotoxins
Crop rotation	Rotate cereals with non-host crops (e.g. legumes, maize-wheat)	Breaks pest/fungal cycles; increases microbial diversity	Reduced *Fusarium* inoculum, lower trichothecenes in succeeding crops (Chen et al., 2023a; Dong et al., 2023)
	Diversified rotations (e.g. potato-maize, inclusion of cover crops)	Enhances structure, suppressive microbial taxa	Lowers *Alternaria*, *Colletotrichum*, *Fusarium* incidences (Li et al., 2023)
Planting density	Moderate density (e.g. ~28,000 plants/acre; wide rows)	Improved air circulation; reduced canopy humidity	Minimizes aflatoxin and ear rot risk while maintaining yields
	Lower seeding rates or strategic row spacing (30" vs 40")	Better light penetration; lower fungal favorable microclimate	Reduced ear mold and mycotoxin levels in corn and cereals (Saleem et al., 2025)
Combined approach	Rotation + optimal spacing	Synergistic benefits: healthy soil + healthy canopy	Suppresses soilborne pathogens and infection risk effectively

2.2.2 Weed management

Weed is any undesirable plant that grows in agricultural fields or other cultivated areas where it is not needed. It may be a remnant from a previous crop or volunteer plants. Weed management is critical in agriculture, not only for optimizing crop yield but also for minimizing disease risks associated with fungal infections. Weeds compete with crops for essential nutrients, water, and light. They also provide food, shelter, and reproductive sites for various pest organisms, including plant pathogens and insects serving as alternate hosts for these organisms (Bhowmick et al., 2018). Thus, they serve as a reservoir for fungal spores, which can lead to infection of crops and subsequent mycotoxin production.

Farmers use different methods to effectively control weeds in their farms before planting or at a certain growth stage of their crop (Table 5). They sometimes use tillage as an effective method for controlling weed growth and reducing seed banks. Depending on the type of agricultural system, complementing tillage with other weed control methods, such as consistent mowing, will prevent weeds from reaching the reproductive stage, reducing seed production and weed reestablishment. It is important to note that excessive tillage may adversely affect beneficial soil fungi and degrade the soil structure over time (Saleem et al., 2022).

Table 5 Weed management and its influence on fungal disease risks

Control strategy	Mechanism	Effect on weeds and microenvironment	Impact on fungal risk/mycotoxins
Tillage and mowing	Disturbs weeds; reduces seed bank and biomass	Lowers weed cover but can disrupt soil fungi	Fewer fungal reservoirs; improved aeration
Mulching and cover cropping	Suppresses weeds; alters soil microclimate	Shades soil; improves structure; releases allelochemicals	Reduces viable weed-based fungal reservoirs
Selective herbicide use	Targets specific weed patches	Controls resistant weeds without major ecosystem disruption	Limits competition; removes fungal harbor plants
Biological control agents	Introduces specific fungal or bacterial weed pathogens	Lowers weed densities ecologically	Reduces potential reservoirs; avoids herbicide residues

Farmers have, over the years, adopted the use of cultural practices to control weeds. Incorporating organic mulches, such as straw, wood chips, and compost, or utilizing cover crops like rye and sunn hemp have been used effectively in suppressing weed growth while also limiting fungal accumulation on the soil surface. Notably, certain cover crops from the Brassicaceae family release allelopathic compounds, which inhibit soil-borne pathogens (Santos et al., 2021).

Spot treatments with selective herbicides minimize weed populations without broad-spectrum ecological disruption, reducing competition and potential fungal reservoirs (Chen et al., 2023b). Use of bioherbicides, fungi, or bacteria that specifically antagonize weeds can minimize weed biomass without relying on chemical herbicides (Den Breyeen et al., 2022; Harding & Raizada, 2015). However, care is needed to avoid interactions with crop pathogens and beneficial fungi. Thus, the risk of mycotoxin contamination can be reduced by implementing effective weed management strategies to maintain crop health and reduce the prevalence of mycotoxigenic fungi and subsequent mycotoxin contamination of crops.

2.2.3 Field hygiene practices

Maintaining clean and tidy fields is a significant preventative measure. Regularly removing crop debris and diseased plant materials decreases the sources of fungal inoculum and diminishes the overall pathogen presence in the field. Enhanced field sanitation practices as found in Table 6, such as disinfecting tools and equipment, can significantly reduce the likelihood of mycotoxin-related issues (Oliver et al., 2021).

Table 6 Hygiene practices and their impact on inoculum and disease risks

Practice	Mechanism	Impact on inoculum and disease risk
Removal of crop debris	Eliminates residue that harbors fungal spores	Lowers primary inoculum and disease carry over
Leaf shredding/residue incorporation	Accelerates decay and reduces pathogen survival estimated	Suppresses crop residue-borne fungal inoculum
Tool and equipment sanitation	Prevents cross contamination between fields	Limits pathogen spread and introduction of resistant pathogens

2.2.4 Surveillance and monitoring

Proactive crop monitoring is imperative for early detection of fungal infections and diseases. Utilizing advanced field sensors and technology, such as drones and soil moisture sensors as found in Table 7, enables farmers to keep a close watch on plant health. This timely intervention can help implement immediate management strategies to address potential threats before they escalate (Pérez et al., 2023).

2.2.5 Integrated pest management

Holistic approach that combines various methods to manage pest populations while minimizing the use of chemicals has been summarized in Table 8. Although chemicals are still used to control plant diseases, excessive use can increase production costs, fungicide resistance, and environmental pollution. By implementing practices such as natural pest predators, crop scouting, and

Table 7 Benefits and limitations of different crop monitoring methods

Monitoring method	Technology/tool	Strengths	Limitations
Manual scouting	Visual inspection and symptom recording	Cost-effective, specific diagnosis	Labor-intensive, limited spatial coverage
Drone-based imaging	RGB, multispectral, thermal, LiDAR sensors	Large-area, high-resolution detection; early stress signals	Costs and technical expertise needed
ML/DL disease modeling	CNN, deep learning on imagery	High accuracy; automated disease classification	Needs training datasets and calibration
Soil and canopy sensors	IoT devices measuring humidity, moisture	Continuous environmental data; predictive risk insight	Sensor maintenance and data management

Table 8 IPM strategies and their impact on crops

IPM component	Approach/tool	Impact on pest damage and fungal risk
Biological control	*Beauveria*, *Metarhizium*, *Trichoderma* agents	Suppresses insect pests that damage plants and allow fungal infection; reduces chemical reliance
Cultural/mechanical practices	Crop rotation, sanitation, residue removal	Lowers both insect vector density and fungal inoculum
Field scouting and thresholds	Monitoring pest levels, using action thresholds	Limits pest damage and secondary fungal colonization
Targeted chemical application	Spot treatments instead of broad spraying	Minimizes fungicide resistance, reduces environmental exposure
Pest monitoring systems	Spatial/temporal networks for early detection	Reduces unnecessary pesticide use with maintained control

targeted insecticides, farmers can protect crops from pest-related damage that creates openings for harmful fungi. Healthy, resilient plants are less prone to pest infestations, lowering the risk of fungal infections and associated mycotoxin contamination (García et al., 2023).

3 Interventions post harvest

It is difficult to come by feed ingredients or finished feed that are mycotoxin-free. Warm, moist environments of temperatures greater than 25°C and humidities greater than 85% are typically conducive to fungal growth; therefore, these conditions introduce a higher potential for mycotoxin production. Although pre-harvest interventions play a crucial role in reducing fungal growth and contamination when crops are growing in the field, post-harvest strategies deter mycotoxin development and accumulation during storage, processing, and distribution. Grains contaminated by mycotoxins are influenced by factors such as moisture content at harvest, holding time before drying, storage type and quality, insect damage, and infestation. Insufficient drying during harvest and high moisture of feed ingredients, such as corn, often lead to hot spots and fungal growth during storage.

New ingredients coming in should be tested either by the supplier before shipping or verified at receiving, which should then be stored properly to prevent fungal growth. Moisture and temperature should be controlled, regular cleaning of equipment, transportation carts, storage bins, and sanitation of feed mills is vital in controlling mycotoxins.

Feed mills, ideally, should also retest the finished feed for mycotoxins before the feed is delivered to the farm. Rapid mycotoxin testing kits such as lateral flow and ELISA could be used to screen for mycotoxins at the farm and the feed mill for quick results. Sampling, sample preparation (grinding), and testing often takes about 30 min per truck to get the results to determine if the grains have to be accepted, rejected or diverted. Waiting for long periods to get results often leads to congestion of truck lines, economic risk for farmers especially if their loads are rejected, downgraded, or diverted. Positive samples are sent to analytical labs for reconfirmation and accurate quantification, which often takes about 2–48 h to get results. Feed mills should have a hazard analysis and critical control point (HACCP) system of approach to be able to identify other risk factors. Feed additives such as vitamins have grain products in them as carriers; therefore, it is important to check them for mycotoxins, as they can be an unexpected source of contamination. Samples should be tested frequently to know when there is a problem, as a safety margin.

3.1 Pre-feed formulation interventions

3.1.1 Storage management

Reducing mycotoxin content in feed involves several strategies. The separation of contaminated materials from healthy feed commodities can be achieved by removing damaged, discolored, lightweight or moldy sections of grains and burning them. In some operations, the contaminated grains are fed to some insects that detoxifies the toxins and the insect meal generated is incorporated into animal feed in regions where insect meal is allowed in animal feed. Proper storage and handling to prevent fungal growth are effective measures of reducing mycotoxin contamination. Proper storage management can be done by controlling the temperature, humidity, and moisture levels in the environment (Peraica et al., 2002). Reducing the oxygen level in stored grains can also prevent some storage mycotoxins such as AFs (Magan & Aldred, 2007). Moisture content is a measure of water related to the drying of products, and it is often expressed as a percentage. Water activity (0.70) a measure of water available for microbial use. A water activity of 0.70 helps prevent spoilage and allows for long term storage. An example of environmental conditions conducive to mycotoxin-specific production in certain grains can be found in Tables 9 and 10. To minimize the risk of mycotoxin development, Magan & Aldred (2007) recommend hermetic storage systems and moisture-absorbing materials as effective strategies for extending the shelf life of stored grain. With proper conditions, grain can be stored for up to a decade.

3.1.2 Decontamination techniques

After pre-harvest mycotoxin interventions, if animal feed products test positive for mycotoxins or as a proactive measure, decontamination is the next step

Table 9 Common pre-harvest grain mycotoxins and their optimum conditions for fungal growth and mycotoxin production

Mycotoxin	Typical producer fungi	Optimum temperature (°C)	Optimum water activity (aw)	Main grain/host
Fumonisins	*Fusarium verticillioides*, *F. proliferatum*	15–30	0.90–0.995	Corn, wheat, sorghum, barley, oats
Zearalenone (ZEN)	*Fusarium graminearum*, *F. culmorum*	~25	0.96	Maize, corn, wheat, barley, rye
Deoxynivalenol (DON)	*Fusarium graminearum*, *F. culmorum*	26–30	0.995	Corn, wheat, barley, oats
T-2 toxin	*Fusarium sporotrichioides*, *F. langsethiae*	12–24	0.88–0.96	Wheat, barley, corn, oats, rye, rice, beans
Ergot alkaloids	*Claviceps purpurea*	15–25	~0.80	Wheat, rye, barley

Source: Adopted from Milani (2013).

of action. Effective decontamination methods must inactivate or remove feed toxins, leave no harmful residues, preserve nutritional value, and prevent regrowth, all while being cost-effective. Common post-harvest methods for controlling mycotoxins in animal feed are categorized as physical, chemical, and biological, which can destroy, suppress, modify, or adsorb the toxins (Assaf et al., 2017; Karlovsky et al., 2016; Muhialdin et al., 2020).

3.1.2.1 Physical decontamination

Physical methods provide practical, cost-effective, and scalable solutions that can be applied at multiple stages of the feed production and storage process. These methods include drying, cleaning, heat treatment, extrusion, and Ultraviolet (UV) treatment, which aim to either prevent mycotoxin-producing fungi's growth or minimize the concentration and bioavailability of existing mycotoxins in feed and ingredients.

Drying involves reducing the moisture content of newly harvested crops to reduce fungal growth, which would in turn assist in reducing the potential for mycotoxins. This should be done immediately after harvest to minimize mycotoxin contamination risks. Mycotoxigenic fungi such as *Aspergillus, Fusarium, and Penicillium* species proliferate in moist environments; hence, lowering the moisture content below critical thresholds (i.e., below 13–14%) significantly inhibits fungal growth and subsequent toxin production (Bankole & Mabekoje, 2004). Some studies suggest that quick drying using high

Table 10 Common post-harvest grain mycotoxins and their optimum conditions for fungal growth and mycotoxin production

Mycotoxin	Typical producer fungi	Optimum temperature (°C)	Optimum water activity (aw)	Main grains/commodities
Aflatoxins	*Aspergillus flavus*, *A. parasiticus*	~33	0.99	Corn, peanuts, wheat, cotton seeds, nuts
Ochratoxin A	*Aspergillus ochraceus*, *Penicillium verrucosum*	15–30	0.85–0.98	Wheat, barley, oats, soy, beans
Citrinin	*Penicillium citrinum*, *P. expansum*	20–30	0.75–0.85	Wheat, barley, corn, rice
Alternaria toxins (AOH, AME, TeA, ATX)	*Alternaria alternata*, *A. tenuissima*	5–30	0.90–0.98	Corn, wheat, oats
Patulin	*Penicillium expansum*	20–25	0.95–0.99	Apples, pears, fruit-derived feeds
Penicillic acid	*Penicillium aurantiogriseum*	20–25	0.95–0.99	Corn, wheat, barley
Roquefortine C	*Penicillium roqueforti*, *P. crustosum*	20–25	0.95–0.99	Cereals, silage, stored grains
Mycophenolic acid	*Penicillium roqueforti*	20–25	0.95–0.99	Silage, stored cereals
Gliotoxin	*Penicillium* spp., *Aspergillus fumigatus*	25–30	0.95–0.99	Stored grains, silage, compost
Penitrem A (tremorgenic)	*Penicillium crustosum*, *P. commune*	20–25	0.95–0.99	Moldy cereals, nuts, food waste, silage
Verruculogen (tremorgenic)	*Penicillium verrucosum*, *P. crustosum*	20–25	0.95–0.99	Cereals, silage
Thomitrems A & E (tremorgenic)	*Penicillium thomii*	20–25	0.95–0.99	Cereals, silage, stored feed

Source: Adopted from Milani (2013); Mannaa & Kim (2017); Pitt & Hocking (2009); Mostrom (2021); Waratuke (2017).

temperatures of between 100–180 °F for lengths of 6–48 hours is reported to lower moisture content to less than 20%, thus preventing fungal growth and its accompanying mycotoxin contamination in grains. This process can harm or alter the nutrient contents of the corn (Timm et al., 2020). It is well established that cereal grains, such as corn, which form a major component of animal feed, are typically received into the mill in bulk and often mixed with dust, debris, and foreign material due to the threshing and subsequent handling methods.

Cleaning is a critical step in feed processing because it can reduce fungal growth. The removal of foreign materials in grains is one of the most effective ways to reduce the risk of mycotoxin contamination. Several studies have demonstrated that mycotoxins tend to concentrate in grain dust, and exposure to this dust can increase health risks in animals (Pietri et al., 2012; Hartmann et al., 2020). Effective dust collection and separation systems can help divert mycotoxins into fine particulate fractions, thereby preventing their inclusion in raw materials or finished products (Čolović et al., 2019). The removal of impurities such as stones, dust, pieces of wood, seeds of weeds, corn cobs, husk, etc during the cleaning phase can effectively reduce the risks of fungal growth during feed processing and storage (Kabak et al., 2006; Schaarschmidt and Fauhl-Hassek et al., 2021). It is important to note that separation systems are also effective for eliminating broken kernels, which tend to have higher mycotoxin concentrations than intact ones. Some grains undergo milling before storage, separating tissues into bran, germ, and endosperm fractions through sieving and aspiration. While milling generally reduces mycotoxin levels, results vary by cereal batch and fraction type. It should not be considered a primary mycotoxin mitigation strategy (Schaarschmidt & Fauhl-Hassek, 2021). Furthermore, the clean material from milling usually goes to human consumption. Techniques like screening and gravity separation are more frequently used than air classification for removing broken kernels and coarse impurities (Čolović et al., 2019). Other conventional sorting methods typically rely on gravity separation, centrifugal force, and air flotation (Pascale et al., 2020). For example, sorting and cleaning have been reported to lead to a 29–69% reduction of FUM in corn samples, a 23–90% reduction in DON, a 25–80% reduction in T-2 toxin (Pascale et al., 2011; Sydenham et al., 1994; Tibola et al., 2016; Trenholm et al., 1991) . Additionally, cleaning can result in a mass loss of about 1–10%, depending on the intensity of the cleaning. The cleaning involves the removal of unwanted materials such as weeds, foreign materials, cobs, husk pieces, broken kernels, damaged kernels, moldy kernels, dust, and fines (Pascale et al., 2022).

Thermal treatment during feed processing, such as extrusion and pelleting, can reduce the activity of some biological pathogens such as fungi (Huss et al., 2018; Jones, 2011). Optimized storage conditions are closely linked to drying, with temperature and humidity being two key variables that influence the survival and activity of fungal spores. Storage facilities for feed and ingredients should be well-ventilated, insulated against external moisture, and routinely monitored to maintain stable internal conditions. Heat treatment can be effective in reducing mycotoxin contamination (Murphy et al., 2006) (Table 9).

Ultraviolet-C (UV-C) radiation is another physical method employed in effectively controlling external mycotoxin contamination and levels in grains post-harvest. UV-C treatment has proven to be an effective strategy for reducing levels of mycotoxins, including AFs, patulin, ochratoxin A, and DON in grains (Jubeen et al., 2012; Tikekar et al., 2014; Popović et al., 2018). Ferreira et al. (2021) observed that, in the absence of UV-C treatment, the total fungal colony count increased by 63% in brown rice, 163% in black rice, and 4% in red rice after storage. Additionally, irradiation using Gamma and electron beams is reported to degrade mycotoxins (Pankaj et al., 2018; Mohamed et al., 2022). Ozone treatments can effectively degrade mycotoxins such as AFs, DON, ZEA, and FUM (Conte et al., 2020; Sujayasree et al., 2022). High-voltage atmospheric cold plasma producing reactive gas species can degrade AFs by over 60% through brief exposure to ozone and nitric oxide (Javed et al., 2025; Tang et al., 2024). While effective, these treatments can be costly, inefficient, and sometimes potentially hazardous to operators.

3.2 During feed formulation interventions

3.2.1 Mycotoxin decontamination

3.2.1.1 Adsorbents

These involve the use of substances to adsorb or transform mycotoxins into less toxic metabolites to reduce the risk associated with health hazards in animals and humans. Some adsorbents, such as Zeolite, bentonite, montmorillonite, hydrated sodium calcium aluminosilicate, polymers, are effective in decontamination of mycotoxins, whereas others such as kaolinite, limestone, talc, inorganic phosphate adsorbents are less effective due to low binding to the toxins, poor adsorptive ability, poor interaction, and minimal surface area charge (Elliott et al., 2020). The differences in the efficacy of these different adsorbents in animal feed to mitigate the negative impacts of mycotoxins often create differences or inconsistencies in research results. In the past few years, various adsorbent materials have been evaluated for their potential to bind mycotoxins in grains and animal feeds. The adsorbents use chemical interactions like van der Waals forces and hydrogen bonds, along with pore structure, to bind with mycotoxins (Di Gregorio et al., 2014). Activated charcoal, e.g., has non-specific binding characteristics but may also decrease nutrient availability by binding vitamins or amino acids (Kihal et al., 2022) (Table 10).

The addition of adsorbents to animal feed can help bind the toxins and help limit the uptake of toxins in the gastrointestinal tract (GIT), and facilitate the elimination of mycotoxins from the system. Inorganic adsorbents used in animal feed include phyllosilicates (clay mineral adsorbents), e.g., hydrated sodium aluminosilicate and bentonites. Other mineral-based adsorbents include zeolites. An adsorbent that is able to bind to more than a single mycotoxin, with a high adsorption rate, and does not bind to nutrients in feed is most desirable. Other products used include yeast cell wall products and synthetic polymers (e.g. polyvinylpyrrolidone and cholestyramine). The addition of feed additives in animal diets is common as they act by binding the toxins in the GIT of the animals and excreting them. Feed additives, such as clay minerals, yeast cell walls, and prebiotics (bentonite, montmorillonite, B-glucans, and mannan oligosaccharides), have been shown to bind multiple mycotoxins in the gut of animals (Kabak et al., 2006; Phillips et al., 2008; Yiannikouris & Jouany, 2002). Most mineral adsorbents tend to be most effective against AFs, and modified clays can adsorb other mycotoxins such as zearalenone and ochratoxin (Papaioannou et al., 2005; Wan et al., 2013).

3.2.2 Biological detoxification

This involves transforming mycotoxins into less harmful metabolites using biological agents such as enzymes and microorganisms. Enzyme function is largely determined by the structure and arrangement of the active site, a small, specialized region within the protein that interacts with specific substrates and facilitates their chemical transformation. This active site includes a catalytic center and a binding site, both essential for the enzyme's activity. Certain types of enzymes, bacteria, and yeast can bind or degrade mycotoxins (Adebo et al., 2022; Kabak et al., 2006). These enzymes are mostly specific to some mycotoxins and can speed up the degradation process. Enzymatic detoxification of mycotoxins is currently widely explored due to its advantages such as non-interference with nutrients and the involvement with bacteria, molds, and yeasts (Hathout & Aly, 2014; Wang et al., 2019). Microbial cell wall adsorbents, such as yeast, can bind mycotoxins by reducing their bioavailability.

Many studies have not fully identified the intermediate and final metabolites produced during the detoxification process. Evaluations of safety and efficacy must include an analysis of these by-products to ensure they are non-toxic and do not introduce new risks. Additionally, there is a significant gap in assessing these biologics under commercial production conditions. Most studies involving these biologicals are conducted in vitro using Petri dishes, 96-well plates, or small-scale feed bins and results are not readily translatable to commercial production systems (Liu et al., 2022b). When trials are performed in vivo, diets are usually prepared as mash. Although laying hens can be fed mash diets, pig and broiler chicken diets are predominantly pelleted, requiring exposure to high temperatures during feed processing (Coradi et al., 2016; Myers et al., 2013). Conversely, these high temperatures may reduce the impact of the biologics added to the feed to mitigate mycotoxins. Thus, it is important to investigate the effectiveness and safety of these biologics in real-world applications such as commercial crop production, grain storage, and animal feeding prior to widespread adoption and their stability during pelleting.

3.2.2.1 Chemical detoxification and suppression

Chemical agents can be used in animal feed to improve feed safety; however, it is important to note that the legality of the use of these products can vary widely by country. Oxidizing agents and bisulfate are commonly used in animal feed to suppress bacteria and mold/fungus growth (Cochrane, 2015; Johnson et al., 2011). Organic acids or blends used in feed to inhibit fungal growth in finished feed and feed ingredients, but are not very effective against mycotoxins that are already present in the feed (Lorán et al., 2022; Satterlee et al., 2023). The most widely used is propionic acid (Kabak et al., 2006), while others such as ammonia, copper sulfate, and benzoic, formic, and sorbic acids are also used in controlling fungal growth at varying concentrations for different mycotoxins. The use of organic acids such as propionic acid during storage can reduce or suppress the growth of fungus/mold, especially during storage (Kabak et al., 2006). Alkaline products, such as sodium carbonate, ammonia, sodium hydroxide, and potassium hydroxide, can be used to prevent fungal growth in feed and feed products. Feed additives (commercially available feed additives). Polyphenols in natural oils that are sometimes added to feed products can destroy the cell wall and cell membrane of the microorganisms due to their antifungal properties (Cai et al., 2022; Esper et al., 2014). The main issue with the use of such products is the strong odor, palatability of the products that have been treated with the chemicals and the corrosive threat to feed bins, silos, and feed lines on farms. Additionally, chemicals can also alter the nutritional properties of feed. While fungicides are commonly used, they can be harmful to beneficial fungi that are part of a healthy soil microbiome and compete with mycotoxin-producing fungi. Overuse of fungicides is discouraged because it can lead to increased resistance (Hayes et al., 2014).

3.2.2.2 Nutritional interventions

Research has demonstrated as shown in Table 11, that dietary supplementation of animal feed with antioxidants (e.g. vitamins A, B1, C and E), and some minerals help reduce the negative impact of certain toxins on farm animals (Gbore and Adu 2017; Khan et al., 2014; Nagaraj et al., 1994; Zhao et al., 2019).

Table 11 Categories of feed additives targeted against fungal growth and mycotoxin mitigation in farm animals

Additive	Example	Effectiveness	References
Adsorbing agents	Clay mineral	Mycotoxin reduction: AFB1-50% ↓ ZEN ↓ FUM ↓ T2-toxin ↓	Bhatti et al. (2018)
	Yeast cell walls	Aflatoxin- 80% ↓ ZEN- 41% ↓ OTA-26% ↓ T-2 Toxin-30% ↓	Murthy et al. (2002); Kolawole et al. (2019); Kolawole et al. (2019); Murthy et al. (2002)
	Polymers	DON -3.5% ↓ ZEN >70% ↓ OTA -50% ↓ AFB1 - >35% ↓ FB2 - >30% ↓	Hernández-Patian et al. (2018)
	Agric waste products: Grape pomances, Almond hulls.	AFBI-1.2-2.9 ug/mg ↓ ZEN- 1.3-2.9 ug/mg ↓	Greco et al. (2019)
Modifiers	Bacteria	AFB1 ↓ ZEN ↓	Kabak et al. (2006); Avantaggiato et al. (2014); Vila-Donat et al. (2018)
	Fungi	AFB1 ↓	Xu et al. (2022)
	Enzymes	DON ↓ OTA ↓ AFB1 ↓ ZEN ↓	Martinez et al. (2019); Zhu et al. (2016); Haque et al. (2020)
Antioxidants	L-Threonine Vitamins (eg. A, B_1,C and E), Selenium, curcumin carotenoids, Silymarin, alpha lipoic Amino acids (eg. methionine, glutamic acid, arginine, aspartate and lysine). Vitamin E, silymarin, curcumin, soybean isoflavone Retinol, ascorbic acid, alpha-tocopherol, silymarin and soybean isoflavone	AFB_1-Reduce negative effect of toxin on farm animals Reduces side effects of mycotoxins in animals DON-Helps boost immune function of farm animals FUM-Reduces oxidative stress in animals ZEN- Inhibit estrogen toxicity toxin	Mesgar et al. (2022); Khan et al. (2014); Zhao et al. (2019); Gbore and Adu (2017); Liu et al. (2022); Nagaraj et al. (1994); Gradelet et al. (1998); Liu et al. (2022); Ledur and Santurio (2020); Wang et al. (2018); Liu et al. (2022); Gao et al. (2018)
	Grape extract	AFB1- improved broiler performance	Hassan et al. (2023)

(*Continued*)

Table 11 (*Continued*)

Additive	Example	Effectiveness	References
	Essential oil	OTA-95% ↓ FUM- 51-87% ↓ AFB1-97% ↓ DON- 72% FB1	Aroyeun et al. (2009); Tian et al. (2019); Gorran et al. (2013); Perczak et al. (2019); Xing et al. (2014)
Organic acids	Propionic	FB1 ↓ T-2 toxin ↓	Dazuk et al. (2020)
	Citric	OTA-100 ↓ Citrinin-100 ↓	Awuchi et al. (2023)
	Butyric	AFB1-100% ↓	Moon et al.(2018)
Essential oils	Cinnamon	FB1 ↓ OTA ↓	Xing et al. (2014); Yin et al. (2020)
	Oregano	OTA ↓ AFLA ↓ ZEN ↓	Pattono and Gai (2020); Kocić-Tanackov et al. (2012)
	Lemongrass	OTA ↓ ↓ AFLA	Abd-El Fattah et al. (2010)

4 Conclusion and future trends

The global production of animal protein primarily comes from farm animals, such as ruminants, swine, poultry, and aquaculture. Feed costs represent a significant portion of production expenses, particularly for poultry, where they can account for up to 75% or more. The quality and safety of feed are crucial for optimal animal performance. A major concern in this area is mycotoxin contamination, which can occur in various feed ingredients and pose serious health risks to animals.

Effective mitigation strategies are needed during both the pre-harvest and post-harvest periods to reduce contamination. These strategies may involve improved agronomic practices and appropriate storage conditions. However, implementing these control methods can be complex and may impact feed quality and economic feasibility. A holistic approach to managing mycotoxin contamination is essential to protect animal welfare, maintain production yields, and ensure economic stability in farming. If not addressed adequately, the subtle impacts of mycotoxin contamination can lead to significant economic losses.

To establish an effective mycotoxin management program, there is a need for a holistic approach to mitigate mycotoxin contamination in animal feed. This will require stakeholders' engagement. Stakeholders should use practices, approaches, and methods that have worked while embracing new technologies and methods such as machine learning and predictive modeling to enhance the management of feed mycotoxins. Encourage regular/routine testing throughout the supply chain of cereals and feed to make sure that mycotoxin levels in feed are within the right limits and not only when there is a problem and be proactive about the trends of and extent of mycotoxin issues. Different innovative rapid testing kits capable of testing multiple mycotoxins should be developed and made available to farmers. There has been an increase in testing of animal feed products for mycotoxins in the last few years partly due to the availability of rapid test kits for surveillance. Conventional wet chemistry/ laboratory methods are often used for confirmation. The use of advanced sensitive mycotoxin testing technologies has helped in the detection of emerging mycotoxins. Harvested grains should be properly dried to less than 15% moisture. Bins should be monitored to prevent fungal development during storage. The use of organic acids will continue to be used with new blends with phytochemicals to help reduce some of the harsh effects of organic acids. The industry needs more blends of adsorbing agents to be able to bind many of these toxins. Mitigation approach needs to be affordable, duplicatable, and straightforward.

There is an urgent need for research in the area of testing for mycotoxins in blood metabolites in farm animals because this provides the industry with quick information and be able to offer a quicker solution rather than waiting to confirm with histology information. Oftentimes, this would be too late to offer any meaningful solution.

The increase and use of predictive tools for pre-harvest and post-harvest mycotoxin contamination risk would significantly help the industry There is a need for the development of biomarker technologies for animal blood metabolite testing for multi-mycotoxin exposure. More research is needed on emerging mycotoxins and developing products to counteract their effects on farm animals. The use of advanced technology should be encouraged in mycotoxin mitigation in both pre and post-harvest interventions (e.g. artificial intelligence, predictive modeling, machine learning to predict/forecast mycotoxin incidence). There is a need for automated testing instruments/ devices for multi-mycotoxin simultaneous analysis to standardize testing/ results and improve high throughput processes to lessen turnaround time for results. Consolidation of all mycotoxin surveillance data collected by different entities would be beneficial to farmers. With some of the aforementioned research opportunities, the industry could be well on its way to proactively tackling mycotoxin issues in animal feed.

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6 Where to look for more information

Further information on the subject is divided into preharvest and post-harvest: Readers seeking deeper insight into mycotoxins, their impacts, and current mitigation strategies can draw on several comprehensive resources across scientific literature. Foundational texts such as *Determining Mycotoxins and Mycotoxigenic Fungi in Food and Feed* (De Saeger, 2011) and reviews by Yiannikouris and Jouany (2002) and Pettersson (2004) provide detailed overviews of toxin occurrence, detection, and control in food and feed systems. More recent syntheses, including Ng'ang'a and Niyonshuti (2022) and Magnoli et al. (2019), discuss evolving risk management approaches within the animal feed industry. For readers interested in mitigation technologies, several studies explore mineral- and biologically based detoxification agents (Bočarov Stančić et al., 2024; Satterlee et al., 2023), as well as enzymatic degradation pathways for aflatoxins and fumonisins (Liu et al., 1998; Schmidt et al., 2021; Schmidt et al., 2023; Gomes et al., 2024; Sánchez Arroyo et al., 2024). Genetic resistance remains an important area of research, with traditional breeding successes documented by Guo et al. (2017) and Henry et al. (2009), and emerging strategies emphasizing the deployment of multiple resistance genes to limit pathogen adaptation (Anderson et al., 2010; Mierziak & Wojtasik, 2024). Because environmental stress strongly influences mycotoxin risk, readers may also benefit from broader discussions on climate smart and water efficient agricultural practices (Frimpong et al., 2023; Nguyen et al., 2023; Saikai et al., 2023; Rodríguez Lira et al., 2024; Ali et al., 2025). Together, these resources offer a robust foundation for understanding the complexity of mycotoxin contamination and the diverse tools available for its management.

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