Prevention of Mycotoxin Contamination Risk in the Feed Chain Through GHP and HACCP

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Abstract
Mycotoxin contamination remains one of the most persistent and relevant safety challenges within the feed chain, with significant implications for animal health, the quality of animal-derived products, and, indirectly, public health. Mycotoxins are toxic secondary metabolites produced by filamentous fungi such as *Aspergillus, Fusarium*, and *Penicillium*, which can contaminate plant raw materials and compound feeds at various stages of the production process, particularly during the post-harvest phase. This paper analyses strategies for preventing mycotoxin contamination in the feed chain, focusing on the application of Good Hygienic Practices (GHP) and the HACCP (Hazard Analysis and Critical Control Points) system. Good practice guidelines provide an operational framework for hygiene, handling, storage, and transport, contributing to limiting the factors favoring the development of toxigenic fungi. In parallel, the HACCP system introduces a structured and preventive approach based on hazard identification and monitoring of critical control points (CCPs), tailored to the specific context of each facility or operation. The paper also explores the synergy between the two approaches - GHP and HACCP - and their efficiency in managing the risks associated with mycotoxin contamination, especially in the current context marked by climate change and strict food safety standards. Through an integrated approach, safe feed, animal health, and the confidence of the final consumer can be ensured.

Keywords: animal health, critical control points, food safety, post-harvest contamination, toxigenic fungi.

Introduction

Mycotoxins are toxic compounds produced by various species of molds, such as *Aspergillus, Fusarium*, and *Penicillium*, which can contaminate feed raw materials and plant-based food products [1]. These substances pose a major risk to animal health and, consequently, to food safety for human consumers, as they exert both acute and chronic toxic effects - ranging from liver and kidney damage to endocrine disorders, immunosuppression, or cancer [2]. Mycotoxin contamination is a widespread phenomenon globally, with a significant proportion of agricultural crops frequently exceeding legal limits [3]. Moreover, co-contamination with multiple types of mycotoxins is common in feed, carrying serious implications for animal health, productivity, and the transfer of toxic residues through the food chain [4]. A well-documented example is the excretion of aflatoxin M_1 in milk from cows fed with contaminated feed. Factors such as climatic conditions, agricultural practices, and storage methods significantly influence both the occurrence and the extent of contamination [5]. In particular, climate change fosters the geographical expansion of toxigenic fungi and increases the risk of infestation in regions previously considered safe [6]. In this context, the prevention of mycotoxin contamination has become a priority. The systematic implementation

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of Good Hygiene Practices (GHP) and the Hazard Analysis and Critical Control Point (HACCP) system represents the fundamental pillars of risk management in the feed chain [7]. These two components act complementarily, providing a robust framework for hazard control throughout the entire process - from primary agricultural production to feed administration to animals [8]. The following sections will analyze the main sources of contamination, the contributing factors, and the specific ways in which GHP and HACCP contribute to preventing mycotoxin contamination at each stage of the feed chain.

Sources and Risk Factors of Mycotoxin Contamination in the Feed Chain

Mycotoxin contamination can occur as early as the pre-harvest stage, when toxigenic fungi such as *Fusarium* or *Aspergillus* infect crops intended for feed, particularly cereals (maize, wheat, barley) and oilseed meals (soybean, sunflower) [3, 9]. Warm and humid climatic conditions favor the development of these fungi: for instance, *Fusarium graminearum* produces deoxynivalenol (DON) and zearalenone in infected cereals, while *Aspergillus flavus* contaminates maize with aflatoxins during drought-prone summers, which are increasingly frequent in southern Europe [10]. Risks are further exacerbated by various agronomic factors, including plant water stress, nutritional deficiencies, pest infestations, and the selection of susceptible crop varieties. Agricultural practices therefore play a decisive role in determining the level of fungal contamination in crops intended for feed [11]. Repeated cultivation of maize on the same land, in the absence of effective crop rotation, promotes the accumulation of fungal inoculum in the soil. Furthermore, delayed harvesting, particularly under high-moisture conditions, increases the incidence of diseases caused by fungi of the *Fusarium* and *Aspergillus* genera [12]. Incomplete drying of cereals prior to storage allows further mold development both in the field and in storage facilities. For example, maintaining optimal soil moisture levels in maize cultivation helps reduce fumonisin and deoxynivalenol (DON) content in the kernels [13]. At the same time, pest control measures, such as limiting *Ostrinia nubilalis* infestations, play a preventive role by reducing kernel injuries that facilitate infection by *Aspergillus spp.* Harvesting when kernel moisture drops below 14% reduces the risk of fungal growth; however, kernels harvested at higher moisture levels or those mechanically damaged (e.g., during threshing) are more vulnerable to contamination during storage [14]. Rapid drying of cereals to moisture values below 13-14% is therefore an essential technological measure for preventing the growth of storage fungi, particularly those of the *Aspergillus* and *Penicillium* genera. Storage thus represents an additional critical vulnerability in the feed chain [15]. Improper conditions in silos or storage facilities, such as high relative humidity, temperatures exceeding 20-25°C, and poor ventilation, contribute to the proliferation of toxigenic fungi. In this regard, *Penicillium verrucosum* is known as a source of ochratoxin A in stored cereals, while *Aspergillus spp.* are frequently implicated in aflatoxin contamination of oilseed meals or cereals stored in warm climates [16]. Monitoring studies on feed quality in the European Union indicate that, although exceedances of maximum permitted levels are rare, the presence of subclinical concentrations is frequently reported [3]. In a survey conducted in Italy between 2016 and 2020, out of 722 samples analyzed, only 14 exceeded regulatory thresholds (mainly for DON, aflatoxin B_1, and zearalenone); however, more than half of the samples contained quantifiable levels of mycotoxins. These findings suggest a constant exposure of animals to mixtures of toxins at low doses, below legal thresholds, but potentially harmful over time [17]. Compound feeds, often formulated from cereals, oilseed meals, bran, and premixes, present a specific risk profile. For example, maize is frequently contaminated with DON, fumonisin B_1, and zearalenone; wheat contributes DON and T-2 toxin; while peanut or cottonseed meals are possible sources of aflatoxins [18]. The risk of co-contamination has been confirmed by recent research. A global study published in 2025 by Gruber-Dorninger and colleagues showed that over 90% of compound feed samples for fish contained at least one mycotoxin, and a significant proportion included three or more different types [19]. The combined effects of mycotoxins can be more harmful than those of each toxin individually, due to documented toxic synergies. Therefore, feed quality control requires an integrated approach that also considers the cumulative impact of contaminants [20]. Sources of contamination include fungal infections in the field, mold development during storage, and the use of already contaminated ingredients. Risk factors are diverse climatic, biological, technological, and economic [21]. Effective management requires preventive measures applied throughout the entire production chain, "from farm to fork." In this context, GHP and HACCP represent the most effective tools for prevention and control, aspects that will be detailed in the following chapters [22].

Good Hygiene Practices (GHP) in Mycotoxin Prevention

Good Hygiene Practices (GHP) represent a set of essential operational measures and conditions for ensuring feed safety. They function as Prerequisite Programs (PRPs) within food safety management systems, preventing the occurrence of most hazards and enhancing the efficiency of HACCP plan implementation [23]. Within the feed chain, GHP apply from crop cultivation to transport and final processing. At the farm level, key measures include the use of healthy and resistant seeds, crop rotation, appropriate phytosanitary treatments (e.g., antifungal agents against fusariosis), and rapid drying of cereals to below 14% moisture - one of the most effective measures against fungal growth [24]. Mechanical cleaning of grains reduces mycotoxin contamination by removing damaged kernels, which are the primary carriers of fungal species. Studies have demonstrated reductions in deoxynivalenol (DON), nivalenol, T-2 and HT-2 toxins in wheat, as well as aflatoxins in maize, through sorting and elimination of affected kernels [25]. During storage, silos and warehouses must be cleaned and disinfected before receiving new harvests, protected against moisture and pests, and continuously monitored for internal conditions (temperature and humidity). The application of the FIFO principle (first in - first out) reduces the risk of fungal development. When all these hygiene practices are correctly implemented at the farm level, the initial mycotoxin load entering compound feed factories is considerably reduced [3]. Grain transport must be carried out with clean vehicles, free from residues of previous loads. Combined transport with potentially contaminating products (e.g., chemicals, waste) is strictly prohibited.

Upon receipt of raw materials, GHP requires visual and olfactory inspection as well as rapid testing for the main mycotoxins, even though legally, mandatory testing applies only to aflatoxin B_1 in specific cases [26]. In compound feed factories, the sanitation of equipment (mixers, pelletizers, conveyor belts) is primordial. Increases in mycotoxin levels have been reported during the mixing phase due to residual deposits. Regular cleaning procedures, followed by verification and documentation, are key components of GHP [14, 27]. Although thermal processing (pelleting, extrusion) can partially reduce the mycotoxin load (with reductions of 5-20% for aflatoxin, DON, or fumonisins, depending on process parameters), the effectiveness of these methods is limited. Therefore, prevention remains essential [25]. Pest control is highly significant, as rodents and birds may physically contaminate feed, while insects can carry fungal spores. GHP measures include rodent control, insecticide applications, and active monitoring through traps and inspections [27]. Personnel must be trained to comply with hygiene requirements: wearing clean equipment, avoiding accidental contaminants (e.g., oils, fuels), and reporting any signs of mold. Adherence to these rules is an integral part of the GHP system. The Codex Alimentarius emphasizes that GHP represents the foundation of any effective hazard control system. In many cases, strict application of GHP alone may be sufficient to prevent mycotoxin contamination, thereby reducing the need for HACCP implementation [28]. European guidelines for the cereal and feed sectors (e.g., EFISC-GTP, Coceral) promote a proactive approach - preventing contamination at the source is more effective and cost-efficient than addressing contamination after production [22]. Good Hygiene Practices represent the first line of defense against mycotoxin contamination in the feed chain. By maintaining hygienic conditions, monitoring risk factors, and consistently applying preventive measures, GHP significantly reduces both the likelihood and level of contamination. On this foundation, the HACCP system acts as a complementary tool, directing control toward the remaining critical points and thereby strengthening feed safety along the entire "farm-to-fork" chain [3].

The HACCP System and Critical Control of Mycotoxins

HACCP (Hazard Analysis and Critical Control Points) is an internationally recognized preventive system, originally developed for the food industry and later adapted to the feed sector to control chemical, biological, and physical hazards [35]. In the European Union, Regulation (EC) No. 183/2005 requires feed business operators to implement procedures based on HACCP principles, with mycotoxins classified as major chemical hazards. The system is built upon seven core principles [29] (Figure 1).

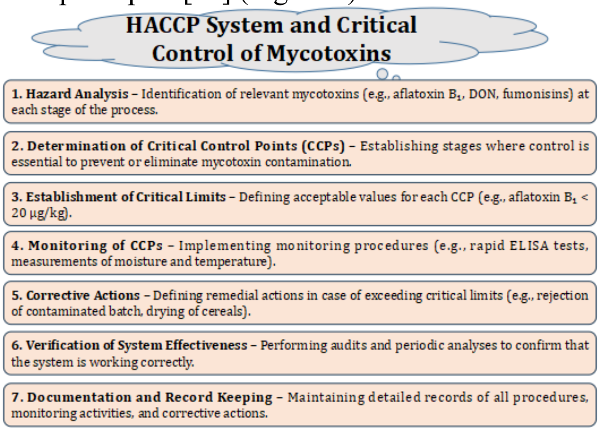

Figure 1. The fundamental principles of the HACCP system (Hazard Analysis and Critical Control Points).

The application of HACCP to mycotoxin risk requires hazard analysis at each stage of the feed chain, from the reception of raw materials to the dispatch of the finished product. In the case of mycotoxins, this analysis relies on scientific data (e.g., maize highly prone to fumonisins and DON; soybean - to aflatoxins), the company's historical records, and current regulations (maximum limits and tolerance guidelines) [30]. Following the hazard analysis, significant hazards that require specific measures within the HACCP plan are identified. The most frequent include aflatoxin B_1 (high toxicity and strict legal threshold - max. 20 µg/kg in most feeds), highly prevalent *Fusarium toxins* (DON, fumonisins, ZEN - problematic even at moderate concentrations), and, in some cases, emerging/masked mycotoxins (e.g., enniatins, beauvericin), noted as potential cumulative risks [3,23]. For example, in a feed mill producing compound feed for dairy cows, the risk of aflatoxin M_1 in milk (legal limit 0.05 µg/kg) makes aflatoxin B_1 in feed a critical hazard [31].

Once hazards are identified, Critical Control Points (CCPs) must be established. For mycotoxins, CCPs may be less evident than for microbiological hazards [32]. One example is the reception of raw materials, where a critical limit such as "Aflatoxin B_1 < 10 µg/kg in incoming maize" is set, alongside monitoring procedures (e.g., rapid tests for each batch or periodic sampling, with rejection of non-compliant lots). Some organizations also consider cereal drying as a CCP, ensuring a critical grain moisture content of ≤ 14%, above which mycotoxin risk increases exponentially [33].

The HACCP model proposed by Fumagalli et al. highlights CCPs across the entire process flow:

- Pre-harvest: soil moisture (to prevent water stress), insect density (triggering IPM - Integrated Pest Management treatments).
- Harvest: grain moisture content (postponing harvest if too hith).
- Storage: silo temperature and humidity (forced aeration if thresholds areexceeded.
- Processing: mixer hygiene (predefined cleaning frequency) [3].

Each CCP has a measurable critical limit, for example: "silo temperature < 15°C," "relative humidity < 70%," "absence of insect infestation," "aflatoxin B_1 < 20 µg/kg" [26]. Monitoring of mycotoxin CCPs can be carried out either through continuous measurements (e.g., thermometers and humidity sensors in silos connected to alarms) or via periodic inspections and laboratory tests. At the corn reception CCP, samples can be taken every 50 tons and rapid ELISA tests performed for aflatoxin B_1 (criterion: negative color; if positive above the limit - the lot is rejected) [34]. All monitoring activities must be documented in record sheets: temperature logs, mycotoxin analysis reports, visual inspection forms, ensuring HACCP traceability. Corrective actions are implemented whenever a critical limit is exceeded. For example:

- Contaminated raw material batch: segregate, return, or apply an approved treatment (e.g., adsorbents or mixing with a clean batch; deliberate dilution above legal limits is not permitted in the EU) [28].
- Excessive silo temperature: cool by forced ventilation or transfer the grains to another silo.

The HACCP plan must specify the corrective actions, responsible personnel, investigation of the root cause, and measures to prevent recurrence (e.g., ventilation failure, highly contaminated batch) [35]. An important aspect of HACCP is the verification and validation of the plan. For mycotoxins, verification includes periodic analyses of the finished feed to confirm levels remain below limits (e.g., sending samples to an accredited laboratory once per month and comparing results to guideline limits), internal audits (checking monitoring and documentation), and external audits (by authorities or certification bodies, e.g., GMP + or ISO 22000) [30]. HACCP provides a structured, science-based framework for controlling mycotoxin risk, shifting the focus from end-product inspection to prevention and continuous control. Its implementation has significantly improved feed safety: although zero contamination cannot be guaranteed, mycotoxin levels remain under control, and deviations are detected and corrected promptly [36].

Synergy between GHP and HACCP in Mycotoxin Control

GHP and HACCP complement each other: GHP provides the hygienic foundation, while HACCP adds targeted monitoring and control. The relationship is often likened to a house's foundation and structure - without a solid GHP base, HACCP becomes ineffective; without HACCP, risks such as mycotoxins are not adequately managed [37] (Figure 2).

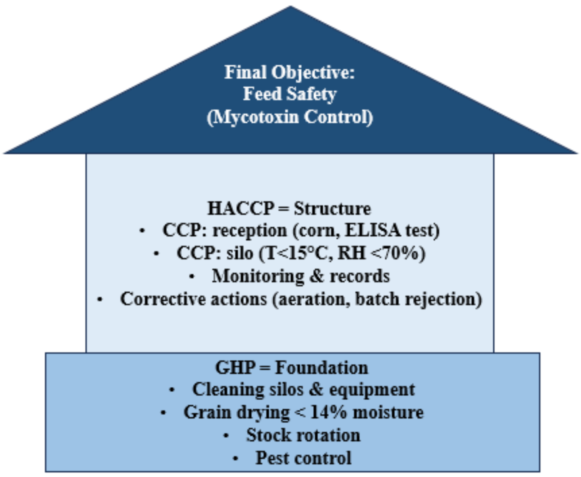

Figure 2. GHP as the Foundation, HACCP as the Structure in Feed Safety.

The Codex emphasizes that HACCP can only be effectively applied where GHP are properly implemented (drying, cleaning, storage). Hamad et al. (2023) demonstrated that companies with rigorous GHP experience fewer non-compliances; for example, a cooperative in Serbia achieved over 95% of batches with DON and ZEN levels below half of the legal limit after strengthening hygiene and drying programs [8]. HACCP ensures adherence to GHP through monitoring and documentation: for instance, mixer cleaning is performed at predetermined intervals by designated personnel, with regular verification. Repeated deviations, such as elevated silo temperatures, indicate shortcomings in GHP application, which must be addressed with appropriate corrective measures [32]. An integrated FSMS (GHP + HACCP) exhibits superior effectiveness, particularly in the context of climate change and the emergence of novel mycotoxins (enniatins, moniliformin, *Alternaria* toxins). GHP limit conditions conducive to fungal growth, while HACCP, based on updated risk analyses, can incorporate monitoring of these emerging mycotoxins even in the absence of legal requirements. Some companies voluntarily test for enniatins and beauvericin to validate preventive measures [38]. International standards (e.g., GMP+) require both documented GHP and HACCP plans, treating non-compliances in either as equally serious. In practice, many companies integrate GHP actions (daily cleaning, facility sanitization) as elements that are monitored and verified through testing and audits [22]. A central aspect remains staff training: operators must understand not only the procedures but also the risks they prevent. GHP prevent hazards, HACCP detects and corrects them. Together, they form a complementary and effective system, recognized as the most reliable solution against mycotoxins [39].

Practical Implementation of GHP and HACCP in Mycotoxin Control

Industry Examples

In certified compound feed factories (ISO 22000, FSSC 22000, GMP+), strict reception procedures are essential. For instance, in corn, automatic sampling is conducted, and if aflatoxin B_1 exceeds the internal threshold of 5 µg/kg (stricter than the legal limit of 20 µg/kg), the batch is rejected [3]. In a factory in the Netherlands (Alltech, 2021), applying this rule reduced aflatoxin exceedances in feed from 8% to below 1% [40]. In China, a swine feed producer integrated HACCP for DON control: through rigorous supplier selection and the establishment of a CCP at the mixing stage (limit 1 ppm), DON levels were maintained below 0.5 ppm, reducing the incidence of vomiting syndrome in pigs by 70%. These examples illustrate how GHP (clean raw materials, sanitized equipment) and well-defined CCPs work synergistically to prevent the adverse effects of mycotoxins [24].

Use of Mycotoxin Binders

An increasingly common practice is the use of mycotoxin-binding additives. Bentonitic clays are applied mainly against aflatoxins, while inactivated yeasts can bind multiple types of toxins. These additives are incorporated into HACCP plans when raw material selection alone is insufficient [41]. Gallo et al. (2020) demonstrated that dairy cows supplemented with bentonite counteracted the effects of DON (~0.7 mg/kg) and fumonisin (~1 mg/kg), maintaining milk production and liver health, compared to groups without the additive [6]. In Romania, large pig and poultry farms use these solutions to mitigate the frequent contamination of locally produced maize with DON and fumonisins, maintaining administration records and reporting low mortality and stable performance [42].

Current Challenges

Even with well-implemented GHP and HACCP, significant challenges remain. Comprehensive analyses (HPLC, LC-MS) are costly, contamination is often variable and difficult to capture through sampling, and small farms have limited resources [43]. However, rapid test kits and simplified guidelines facilitate monitoring. A dairy cooperative that systematically rejected maize with >5 μg/kg AFB_1 demonstrated the practical impact of these measures: over five years, no milk sample exceeded the EU limit for aflatoxin M_1, reducing economic losses and protecting the company's reputation [4].

Perspectives and Innovations

Climate change increases contamination risk, particularly aflatoxins in temperate regions and emerging fungal species. Predictive models and adaptive HACCP plans are essential. Innovative solutions include feed detoxification through irradiation, cold plasma, controlled ozonation, or biotechnologies (enzymes and microorganisms capable of degrading toxins) [44]. Concurrently, EFSA highlights the cumulative effects of mycotoxins, which may lead to regulations addressing combined toxins and the use of combined risk indices. Integrating the One Health concept and digitalization (IoT, silo sensors, data analysis platforms) will enable continuous monitoring and proactive interventions, including preventive additive administration in high-risk years [45]. The benefits of integrated application are clear: reduced mycotoxin concentrations in feed, fewer non-compliant products, improved animal performance, and enhanced public health protection. The practical lesson is that success requires combining impeccable prevention (GHP), systematic control (HACCP), and technological innovations (additives, sensors, biocontrol), creating a feed chain that is safe and adaptable even under challenging climatic and economic conditions [3, 46].

Conclusions

The issue of feed contamination with mycotoxins remains complex and has a major impact on animal health and food safety. To mitigate this risk, it is essential to combine general preventive measures, through Good Hygiene Practices (GHP), with the strict monitoring and control provided by the HACCP system. While GHP reduces the initial contaminant load through proper hygiene, storage, and handling, HACCP ensures continuous oversight of critical points and the implementation of corrective actions when limits are exceeded. Practical experience demonstrates that this integrated approach significantly lowers mycotoxin levels in feed and contributes to maintaining livestock performance and the quality of animal-derived products. However, implementation requires adequate resources, personnel training, and adaptation to emerging conditions, such as climate change or the appearance of new mycotoxins. The successful management of this risk depends on the rigorous application of GHP, a robust HACCP plan, and the integration of modern solutions capable of strengthening feed chain safety from producer to consumer.

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