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Review

Mycotoxins in Fish Production and Impact on Fish Health

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Abstract: The aim of this review is to provide an assessment of mycotoxin contamination in fish feed. Focusing on major mycotoxins including aflatoxins, fumonisins, ochratoxins, trichothecenes, and zearalenone, the paper explores their diverse impacts on fish health, from growth inhibition to immunosuppression. It meticulously examines the sources of mycotoxin contamination in fish feed, addressing raw ingredients, storage conditions, and feed manufacturing processes. The review emphasizes the critical role of adherence to Good Agricultural Practices (GAP) and Good Manufacturing Practices (GMP) in preventing mycotoxin risks. Additionally, the paper elucidates mitigation strategies, encompassing the use of mycotoxin-binding feed additives, feed formulation optimization, and technological advancements for early detection. This comprehensive overview serves as a valuable resource for aquaculture practitioners, researchers, and policymakers aiming to enhance the safety and sustainability of fish production amidst mycotoxin challenges.

Keywords: fish; mycotoxins; nutrition; health; immunity; mycotoxin binders.

1. Introduction

In recent years, the burgeoning global demand for fish and seafood has led to an unprecedented intensification of aquaculture practices, significantly impacting the quality and safety of the final product [1,2]. Among the myriad challenges faced by the aquaculture industry, mycotoxin contamination of fish feed has emerged as a critical concern, posing substantial threats to fish health, immunity, and overall production [3]. Mycotoxins, secondary metabolites produced by various fungi, have been identified as potent contaminants in fish feed, leading to adverse effects on growth, immune response, and overall physiological well-being of aquatic organisms [4–6].

This review paper endeavors to provide a comprehensive exploration of the multifaceted impact of mycotoxins on fish production, with a particular focus on major contaminants such as aflatoxins, fumonisins, ochratoxin, trichothecenes, and zearalenone. By delving into the intricate interplay between mycotoxin exposure and fish health, this review aims to shed light on the underlying mechanisms through which these toxic compounds exert their influence. Additionally, it will scrutinize the potential consequences of mycotoxin-contaminated fish products on human consumers and the broader implications for global food safety.

Furthermore, the paper will critically assess current mitigation strategies employed by the aquaculture industry to curb mycotoxin contamination in fish feed. Through an integrative analysis of research findings, this review seeks to contribute valuable insights to the scientific community, aquaculture practitioners, and policymakers, fostering a better understanding of the challenges posed by mycotoxins in fish production and paving the way for the development of effective preventive and remedial measures. As we navigate the intricate web of mycotoxin-fish interactions, the synthesis of existing knowledge presented herein aims to inform and guide future research endeavors toward sustainable and resilient aquaculture practices.

2. A comprehensive examination of mycotoxin contamination of fish feed

The escalating demand for fish and seafood products worldwide has prompted a significant intensification of aquaculture practices [7]. As the aquaculture industry strives to meet the growing needs of the global population, it faces an array of challenges, with mycotoxin contamination emerging as a critical concern, particularly in the context of fish feed [8]. Mycotoxins, secondary metabolites produced by fungi, have been identified as potent contaminants in various agricultural commodities [9], and their presence in fish feed (Figure 1) raises profound implications for fish health, production efficiency, and the safety of seafood products for human consumption [10,11]. In this comprehensive exploration, we delve into the intricacies of mycotoxin contamination in fish feed, examining the types of mycotoxins involved, their sources, the mechanisms through which they impact fish, and the current strategies employed to mitigate these threats.

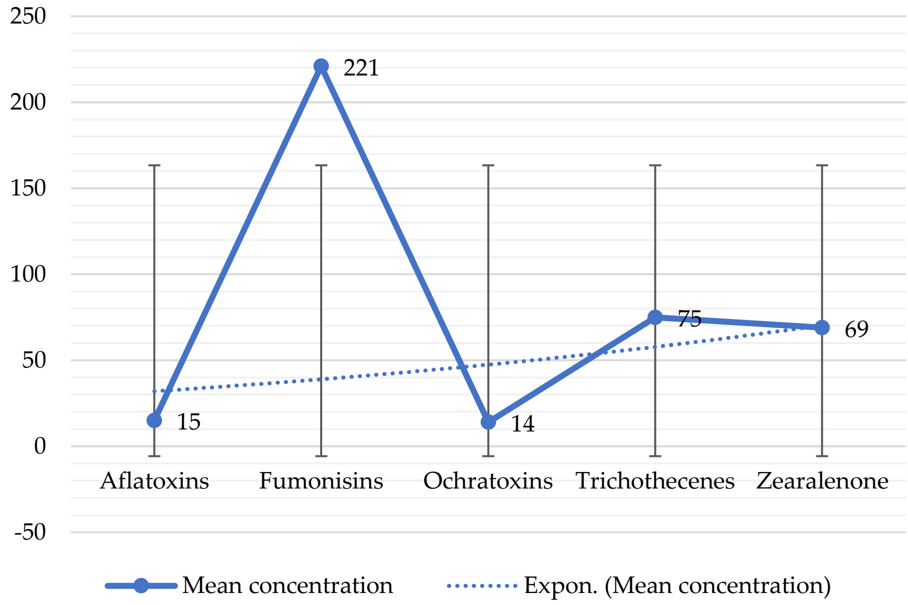

Figure 1. Natural contamination of aquaculture feeds with mycotoxins (µg/kg feed) [12].

Among the diverse array of mycotoxins, aflatoxins stand out as particularly notorious contaminants in fish feed [13]. Aflatoxins are produced primarily by *Aspergillus* species and are known for their potent carcinogenic properties. The susceptibility of fish to aflatoxin exposure varies across species, with catfish and tilapia being notably sensitive. The ingestion of aflatoxin-contaminated feed can lead to bioaccumulation in fish tissues, posing risks to both aquatic health and human consumers [14]. Fumonisins, produced by *Fusarium* species, are another group of mycotoxins that frequently contaminate fish feed [15]. These toxins are implicated in various health issues, including liver and kidney damage, as well as disruptions in sphingolipid metabolism. Understanding the prevalence and impact of fumonisins in fish feed is crucial for mitigating their adverse effects on fish health and the subsequent implications for human consumption [16]. Ochratoxins, produced by *Aspergillus* and *Penicillium* species, have been identified in fish feed, raising concerns about their potential impact on fish health [17]. With nephrotoxic effects and potential carcinogenicity, ochratoxins warrant careful consideration in the context of aquaculture, as their presence can compromise the physiological integrity of fish and the safety of fish products for human consumption [18]. Trichothecenes, produced by various *Fusarium* species, are mycotoxins with immunosuppressive and cytotoxic effects [19]. In the context of fish feed, the impact of trichothecenes on the immune system and overall health of aquatic organisms is a critical area of investigation [20].

Understanding the mechanisms through which trichothecenes exert their influence is essential for developing targeted mitigation strategies. Zearalenone, produced primarily by *Fusarium* species, is known for its estrogenic properties [21,22]. In fish, exposure to zearalenone can lead to reproductive abnormalities and disturbances in the endocrine system [23]. Examining the prevalence of zearalenone in fish feed and its implications for reproductive health in aquatic organisms is essential for ensuring the sustainability of aquaculture practices [24].

3. Sources of mycotoxin contamination in fish feed

The quality and safety of fish feed play a pivotal role in determining the health and productivity of aquaculture systems [25]. One of the major challenges confronting the aquafeed industry is the contamination of raw ingredients by mycotoxins, secondary metabolites produced by fungi [26]. Mycotoxins pose a significant threat to fish health [27], growth [16], and overall aquaculture sustainability [28]. In this comprehensive exploration, we delve into the various raw ingredients commonly used in fish feed formulation and the inherent risks associated with mycotoxin contamination. Understanding the sources and dynamics of mycotoxin contamination in raw ingredients is paramount for the development and implementation of effective preventive measures, ensuring the production of high-quality and safe fish feed for sustainable aquaculture practices.

Mycotoxin contamination often originates in the raw ingredients used in fish feed formulation [29]. Crops such as maize, peanuts, and soybeans, which are commonly used in aquafeed, are susceptible to fungal contamination during cultivation, harvest, and storage (Figure 2).

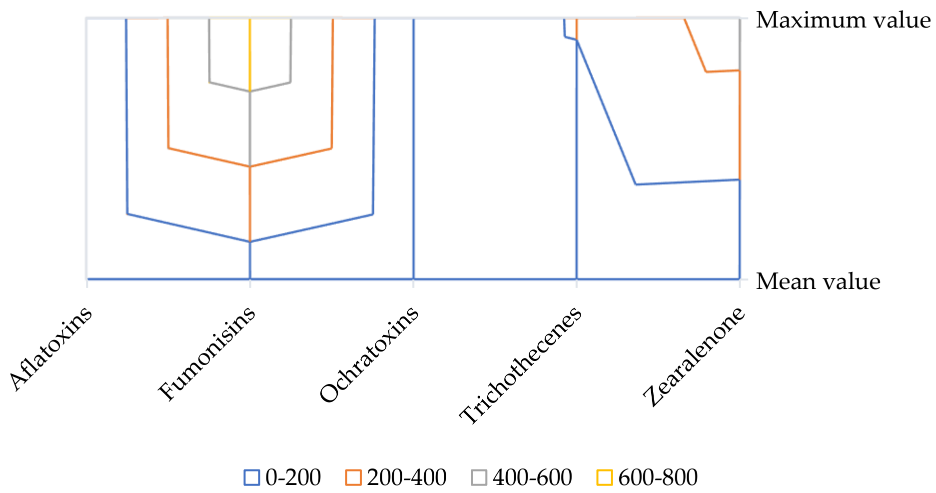

Figure 2. Contamination of the feed ingredients with mycotoxins in the final fish feeds (μg/kg feed) [12].

Understanding the factors that contribute to mycotoxin contamination in these raw materials is crucial for implementing preventive measures at the early stages of feed production. Cereals and grains such as maize (corn), wheat, rice, and barley are primary sources of energy in fish feed [30]. They contribute to the overall structure of the feed and serve as a crucial energy source for fish metabolism [31]. However, these raw materials are particularly susceptible to fungal contamination, making them potential sources of mycotoxins in fish feed. Oil seeds like soybeans, sunflower, and canola, along with their processed meals, are valuable sources of protein and lipids in fish feed [32,33]. These ingredients provide essential amino acids and fatty acids necessary for fish growth and development [34]. Nevertheless, the production and storage of oilseeds are associated with mycotoxin contamination risks, as fungi can proliferate under conducive conditions. Fish meal, derived from fish processing by-products, is a high-quality protein source in aquafeed. While fish meal is prized for its nutritional profile, the raw materials used in its production can also be prone to mycotoxin contamination. This is especially true if the fish processing by-products include offcuts and trimmings from fish with mycotoxin-contaminated feed. Legumes such as peas, lentils, and chickpeas are utilized in fish feed formulations as alternative protein sources [35]. While legumes are nutritionally valuable, they, too, are susceptible to fungal contamination during cultivation, harvesting, and storage. Mycotoxin contamination in raw ingredients often begins in the field, where crops are vulnerable to fungal infestations during cultivation. Factors such as climatic conditions, soil health, and agronomic practices influence the growth of mycotogenic fungi [36]. *Aspergillus*, *Fusarium*, and *Penicillium* species are common culprits, producing mycotoxins such as aflatoxins, fumonisins, and ochratoxins. The combination of various raw ingredients in feed formulations can lead to synergistic effects that amplify the risks of mycotoxin contamination [37]. Different fungi may thrive in specific ingredients, and their mycotoxins can accumulate in the final feed product. The interactive effects of mycotoxins, known as mycotoxin interactions, add complexity to the risk assessment process [38].

The process of feed manufacturing itself can contribute to mycotoxin contamination. Inadequate processing conditions, such as suboptimal temperature and humidity control, can facilitate the growth of mycotogenic fungi and the production of mycotoxins. Examining the critical control points in feed processing and implementing good manufacturing practices are essential steps in minimizing the risk of mycotoxin contamination [39]. In the intricate web of aquaculture production, the manufacturing process of fish feed stands as a crucial determinant of the quality, safety, and nutritional adequacy of the final product. However, the very processes designed to transform raw ingredients into nutritionally balanced pellets can inadvertently contribute to mycotoxin contamination. Feed manufacturing involves a series of intricate processes designed to transform raw ingredients into a palatable and nutritionally complete diet for aquatic organisms [40]. Raw ingredients, such as cereals, grains, and oilseeds, undergo grinding to achieve a consistent particle size. This process enhances the uniformity of the feed and facilitates optimal nutrient utilization by aquatic organisms. However, the grinding process can inadvertently introduce mycotoxins if the raw ingredients are already contaminated. After grinding, various raw ingredients are combined in precise proportions to create a homogenous feed mixture. The mixing process aims to achieve a uniform distribution of nutrients and additives. If mycotoxin-contaminated raw ingredients are present, the homogeneity of the mixture may result in the even distribution of mycotoxins throughout the feed batch. Conditioning involves the application of heat and steam to the feed mixture, improving its physical and nutritional properties. While conditioning contributes to pellet formation and palatability, it may not be sufficient to eliminate mycotoxins, especially heat-resistant ones. In some cases, conditioning can even lead to the concentration of mycotoxins in the final feed. The conditioned feed mixture is subjected to the pelleting process, where it is compressed through dies to form pellets of a specific size. Pelleting enhances feed stability, reduces waste, and facilitates ease of handling [41]. However, the high temperatures involved in pelleting may not always be effective in eliminating mycotoxins, and there is a risk of recontamination during the cooling and storage phases. Pellets exit the pelleting machine at elevated temperatures and are cooled to ambient temperature before packaging. The cooling phase is critical for preventing the degradation of heat-sensitive nutrients. However, it also provides an opportunity for mycotoxin contamination if cooling is not swift or if the cooling equipment is contaminated. In some cases, additional coatings or additives may be applied to the pellets after the pelleting process to improve palatability or enhance specific nutritional aspects [42]. This step introduces another layer of complexity, as the coating materials and additives must be carefully sourced to avoid mycotoxin contamination. The final pellets are packaged and stored under controlled conditions to prevent moisture absorption, maintain nutritional integrity, and deter the growth of mold and fungi. However, if mycotoxin-contaminated raw ingredients are not adequately addressed during the manufacturing process, there is a risk of further mycotoxin development during storage, particularly if storage conditions are suboptimal [43].

The quality of raw materials significantly influences the potential for mycotoxin contamination during feed manufacturing [44]. If raw ingredients, such as cereals, grains, and oilseeds, arrive at the feed mill already contaminated with mycotoxins, the subsequent processes may exacerbate the issue

[39]. Thus, a critical component of mycotoxin risk management is the rigorous testing and screening of raw materials for mycotoxin presence before they enter the manufacturing process. Cross-contamination, wherein mycotoxin-contaminated raw materials introduce mycotoxins into the overall feed mixture, is a key concern during the mixing and pelleting stages. If mycotoxin-contaminated ingredients are not identified and segregated during the mixing process, the resulting feed pellets may contain an uneven distribution of mycotoxins, posing a heightened risk to aquatic organisms. The effectiveness of heat in eliminating mycotoxins depends on the specific type of mycotoxin and its heat stability [45]. Some mycotoxins, such as aflatoxins, are relatively heat-stable and may persist through the conditioning and pelleting processes. Inadequate processing temperatures or insufficient retention time during these heat-based processes can contribute to the survival of mycotoxins in the final feed. The cooling phase, designed to solidify pellets and reduce their temperature, is crucial for preventing nutritional degradation but presents challenges in terms of mycotoxin control. If the cooling process is not rapid or if the cooling equipment is contaminated, there is a risk of recontamination. Furthermore, storage conditions post-manufacturing play a pivotal role in determining the final mycotoxin levels in the feed [46]. Inadequate storage conditions, such as high humidity and temperature, create an environment conducive to fungal growth and mycotoxin production. The absence of robust monitoring and quality control measures at various stages of feed manufacturing can exacerbate mycotoxin contamination risks. Insufficient testing of raw materials, lack of routine analysis during processing, and the absence of quality assurance programs may result in the inadvertent incorporation of mycotoxins into the final feed product [47,48].

Post-production, the storage conditions of fish feed play a pivotal role in determining its susceptibility to mycotoxin contamination. Improper storage practices, including prolonged exposure to high humidity and temperature, create an environment conducive to fungal growth and mycotoxin production. Implementing proper storage practices is imperative for preserving the quality and safety of fish feed [49].

4. Impact of mycotoxin contamination on fish health

Mycotoxin-contaminated fish feed can significantly impair the growth performance of aquatic organisms [50]. Aflatoxins, for instance, are known to cause stunted growth, reduced feed efficiency, and compromised nutrient utilization in fish [51]. Understanding the specific mechanisms through which mycotoxins affect growth parameters is essential for developing strategies to mitigate these adverse effects. As contaminants in fish feed, mycotoxins can disrupt nutrient utilization, compromise immune function, and induce physiological stress, collectively hampering the growth potential of aquatic organisms [27]. One of the primary mechanisms through which mycotoxins impede fish growth is by disrupting nutrient utilization [52]. Mycotoxins can interfere with the absorption, metabolism, and utilization of essential nutrients, including proteins, lipids, vitamins, and minerals. For example, aflatoxins, a group of mycotoxins produced by *Aspergillus* species, can impair protein synthesis and lead to reduced growth rates in fish. The competition for nutrient absorption between mycotoxins and essential nutrients can result in nutrient deficiencies, hindering the fish's ability to meet its metabolic demands for growth [53]. Mycotoxin-induced immunomodulation represents another critical mechanism influencing fish growth performance. Immune system compromise can lead to increased susceptibility to infections and diseases, diverting energy resources away from growth and toward immune defense. Trichothecenes, a group of mycotoxins produced by *Fusarium* species, are known for their immunosuppressive effects in fish [20]. The suppression of immune responses can create a vicious cycle, with compromised health further hindering growth potential. Mycotoxins can induce oxidative stress in fish, disrupting the balance between reactive oxygen species (ROS) production and the antioxidant defense system [54]. Oxidative stress can lead to cellular damage, affecting various tissues and organs crucial for growth [55]. Aflatoxins, for instance, can generate ROS, contributing to oxidative stress and impairing growth-related processes in fish. Mitochondrial function, protein synthesis, and overall cellular integrity can be compromised, directly impacting the fish's ability to achieve optimal growth rates.

Certain mycotoxins possess estrogenic or antiestrogenic properties, disrupting the endocrine system and influencing fish reproductive and growth-related hormones. Zearalenone, an estrogenic mycotoxin, can interfere with the synthesis and activity of reproductive hormones in fish [56]. The disruption of the endocrine system can lead to disturbances in growth, development, and reproductive processes, negatively impacting the overall growth performance of fish. A mycotoxin-contaminated feed can compromise the efficiency with which fish convert feed into body mass, known as feed conversion efficiency (FCE). The disrupted nutrient utilization and immunomodulatory effects of mycotoxins can lead to suboptimal FCE, requiring a greater amount of feed to achieve a given amount of growth. This inefficiency exacerbates the economic impact of mycotoxin contamination on aquaculture operations, as more resources are expended on feed without commensurate gains in fish biomass [57]. Oxidative stress induced by mycotoxin contamination can result in damage to vital organs, further impairing fish growth. Liver and kidney damage are commonly observed consequences, as these organs play pivotal roles in nutrient metabolism, detoxification, and overall physiological homeostasis. The compromised function of these organs can disrupt the fish's ability to process nutrients efficiently and negatively impact its overall health and growth performance. The immune system of fish is highly susceptible to mycotoxin-induced suppression [58]. Trichothecenes, for example, have been shown to compromise the immune response in fish, making them more vulnerable to infections [59]. Investigating the immunomodulatory effects of different mycotoxins and their implications for disease susceptibility is crucial for maintaining the health and resilience of aquatic organisms.

Different fish species exhibit varying degrees of susceptibility and responses to mycotoxin contamination [60]. Catfish and tilapia, for example, are particularly sensitive to aflatoxin exposure, experiencing significant growth inhibition and liver damage [61,62]. Rainbow trout and salmonid species, on the other hand, may exhibit different sensitivities to various mycotoxins, emphasizing the need for species-specific assessments of mycotoxin impact. Understanding the nuances of species-specific responses is crucial for tailoring mitigation strategies and optimizing the selection of fish species in aquaculture operations. Aflatoxins, produced primarily by *Aspergillus flavus* and *Aspergillus parasiticus*, are highly relevant contaminants in catfish farming. Catfish, known for their susceptibility to aflatoxin-induced toxicity, often experience compromised growth, liver damage, and immunosuppression when exposed to aflatoxin-contaminated feed [63]. Aflatoxin B1, the most potent and prevalent aflatoxin, poses a significant risk to catfish health and growth performance [57]. Mitigation strategies in catfish farming involve rigorous testing of raw ingredients, implementing effective feed management practices, and utilizing mycotoxin-binding agents in feed formulations. Tilapia, a widely cultured fish species, is susceptible to fumonisin contamination in feed, primarily from *Fusarium verticillioides* [64]. Fumonisins interfere with sphingolipid metabolism, leading to disruptions in cell membrane function and integrity. Tilapia exposed to fumonisin-contaminated feed may exhibit stunted growth, liver and kidney damage, and increased susceptibility to diseases [65]. Mitigation strategies for fumonisin contamination in tilapia production involve screening and sourcing low-fumonisin raw materials, optimizing feed formulations, and incorporating mycotoxin binders to reduce fumonisin bioavailability. Rainbow trout (*Oncorhynchus mykiss*), a prized species in aquaculture, is susceptible to various environmental stressors that can impact its growth and overall health. Among these stressors, mycotoxin contamination, particularly by trichothecenes, poses a significant threat to rainbow trout farming [66]. Trichothecenes constitute a diverse family of mycotoxins produced by various Fusarium species. Common types include deoxynivalenol (DON), T-2 toxin, HT-2 toxin, nivalenol (NIV), and diacetoxyscirpenol (DAS). These mycotoxins can contaminate a variety of cereal crops, including wheat, barley, maize, and oats, which are commonly used in aquafeed formulations. The prevalence of trichothecenes in these raw ingredients poses a significant risk to rainbow trout farming when contaminated feed is consumed [66]. Trichothecenes, particularly DON, have been linked to stunted growth in rainbow trout. The presence of DON in feed has been associated with reduced feed intake and impaired nutrient utilization, leading to slower growth rates [67]. The mechanisms underlying this growth inhibition involve the disruption of protein synthesis and the modulation of appetite-regulating hormones, impacting the overall metabolic processes essential for growth. The effects of trichothecenes extend beyond growth rates, influencing the efficiency with which rainbow trout convert feed into body mass. DON, in particular, has been shown to reduce FCE by affecting the fish's ability to digest and absorb nutrients efficiently [68]. Suboptimal FCE can contribute to increased production costs and decreased profitability in rainbow trout farming operations. One of the distinctive characteristics of trichothecenes is their immunosuppressive impact. Rainbow trout exposed to these mycotoxins may experience compromised immune responses, rendering them more susceptible to infections and diseases [68]. The immunosuppressive effects of trichothecenes exacerbate the challenges of maintaining optimal health and growth in rainbow trout populations. Trichothecenes can induce hepatotoxic effects in rainbow trout, affecting the liver's structure and function. DON, for example, has been shown to cause histopathological changes in the liver, including vacuolization and degeneration of hepatocytes. Hepatotoxicity further contributes to the overall stress on the fish's physiological systems, impacting growth and overall performance. One of the primary mechanisms through which trichothecenes exert their effects is the inhibition of protein synthesis. DON, as a ribotoxic mycotoxin, targets the ribosomes and disrupts the process of protein translation. This inhibition affects the synthesis of essential proteins involved in growth, immune function, and overall metabolic processes, contributing to the observed growth impairment in rainbow trout. Trichothecenes can modulate the secretion of appetite-regulating hormones in rainbow trout, influencing their feeding behavior [69]. DON, in particular, has been shown to alter the expression of neuropeptides involved in appetite regulation. The disruption of normal feeding patterns and reduced feed intake contribute to the negative impact on growth performance [70].

While the focus of mycotoxin research in the context of fish production often centers on the impact on aquatic organisms, it is imperative to recognize the potential implications for human health. Mycotoxin-contaminated fish products can serve as a route of exposure for consumers, with aflatoxins, in particular, posing carcinogenic risks [71]. Assessing the transfer of mycotoxins from fish feed to fish tissues and evaluating the risks to human consumers are essential components of ensuring the safety of seafood products [72].

5. Mitigation strategies for mycotoxins

The incorporation of feed additives with mycotoxin-binding properties is a commonly employed strategy to mitigate mycotoxin contamination in fish feed [3]. Adsorbents such as clay minerals and activated carbon can bind mycotoxins in the gastrointestinal tract of fish, preventing their absorption and subsequent adverse effects. Evaluating the efficacy of different feed additives and optimizing their use is a dynamic area of research [73]. Mycotoxin contamination in fish feed poses a substantial threat to aquaculture, impacting fish health, growth, and overall production efficiency. One commonly employed and effective strategy to mitigate the adverse effects of mycotoxins is the incorporation of feed additives with mycotoxin-binding properties [39]. These additives act as adsorbents, binding mycotoxins in the gastrointestinal tract of fish and preventing their absorption into the bloodstream. Understanding the intricacies of this mitigation strategy is crucial for aquaculture practitioners seeking to ensure the production of safe, high-quality, and nutritionally balanced fish feeds [74]. Mycotoxin-binding feed additives primarily function through a process known as adsorption. Adsorption involves the physical or chemical adherence of mycotoxins to the surface of the binding agent, preventing their interaction with the digestive and absorptive mechanisms in the gastrointestinal tract. The binding agents possess specific sites that attract mycotoxins, forming complexes that are subsequently excreted from the body. This prevents the mycotoxins from exerting their toxic effects on fish tissues and organs [75]. Several types of binding agents are commonly employed in mycotoxin-binding feed additives (Table 1).

Table 1. Binding agents that are commonly employed in mycotoxin-binding feed additives in fish production [22,53,76–78].

Types of Binding Agents	Effects or Mechanisms of Binding Agents
Clay Minerals	Bentonite: A naturally occurring clay with a high surface area, bentonite is known for its adsorptive capacity for a variety of mycotoxins. Montmorillonite: A type of bentonite, montmorillonite has layered structures that provide an expansive surface area for mycotoxin binding.
Activated Charcoal	Activated charcoal is a porous form of carbon that has been treated to increase its surface area. It exhibits high adsorption capacity for a wide range of mycotoxins.
Silicates	Silicate-based materials, such as hydrated sodium calcium aluminosilicate (HSCAS), have demonstrated mycotoxin-binding capabilities.
Yeasts and Microorganisms	Certain yeast strains and microorganisms, such as Saccharomyces cerevisiae, have been explored for their ability to bind mycotoxins. These biological agents often interact with mycotoxins through specific binding sites.
Enzymes	Enzymes, including carbohydrates and proteases, have been investigated for their potential to modify the structure of mycotoxins, rendering them less toxic or facilitating their elimination.

The effectiveness of mycotoxin-binding feed additives often varies based on the type of mycotoxin and the binding agent employed [79]. Some binding agents exhibit a degree of specificity for certain mycotoxins, while others demonstrate broader selectivity. The choice of binding agent should align with the specific mycotoxin profile encountered in raw ingredients and the desired level of protection against contamination.

Adherence to good agricultural and manufacturing practices is fundamental in preventing mycotoxin contamination at various stages of the feed production process [80]. Implementing proper crop management practices, monitoring raw materials for mycotoxin presence, and ensuring stringent quality control during feed processing are integral components of mitigating the risk of mycotoxin contamination [81]. However, this process is susceptible to mycotoxin contamination, posing a significant challenge to the aquafeed industry. Adherence to Good Agricultural Practices (GAP) and Good Manufacturing Practices (GMP) emerges as a cornerstone strategy in mitigating mycotoxin risks at various stages of fish feed production.

GAP encompass a set of principles and guidelines designed to ensure the safety, quality, and sustainability of agricultural products [82]. In the context of fish feed production, adherence to GAP begins with the sourcing of raw materials. Key principles include site selection and management, seed selection, crop rotation and diversity, and water management. GAP in raw material sourcing involves an in-depth mycotoxin risk assessment, where potential sources of contamination are identified, and preventive measures are implemented. This assessment includes field surveys and monitoring, pre-harvest testing, and quality seed and planting material certification [83].

On the other hand, GMP in fish feed production forms the foundation for ensuring the quality and safety of the final product. Key principles include facility design and layout, equipment and machinery, personnel training, and record-keeping [84]. GMP in feed production involves specific measures to control and mitigate mycotoxin risks at various stages of formulation and processing: Raw material screening, optimized formulation, effective mixing and homogenization, pelleting and conditioning, and cooling and storage [85].

Nowadays there are emerging technologies of mycotoxin detection [86]. Advances in mycotoxin detection technologies, including rapid testing kits, biosensors, and molecular diagnostics, enhance the efficiency and accuracy of mycotoxin screening in raw materials and finished feeds [87,88]. Precision agriculture technologies, such as satellite imaging and sensor-based monitoring, enable more targeted and efficient implementation of GAP. These technologies enhance the ability to monitor fields for fungal infestations and mycotoxin risks. Digitalization and process automation in feed manufacturing contribute to precision control during mixing, pelleting, and conditioning processes. Real-time monitoring of critical parameters [89].

Advancements in biotechnology offer promising avenues for mitigating mycotoxin contamination in fish feed [90]. Bioremediation approaches, utilizing microorganisms capable of degrading mycotoxins, are under investigation as potential strategies to detoxify contaminated feed [39].

6. Conclusions

The review paper provides a thorough and insightful examination of mycotoxin contamination in fish feed, shedding light on the diverse range of mycotoxins, their mechanisms of action, sources of contamination, and strategic mitigation approaches. It serves as a valuable resource for aquaculture practitioners, researchers, and policymakers seeking to enhance the safety and sustainability of fish production in the face of mycotoxin challenges.

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