Occurrence of Fungi and Mycotoxins in Fish Feeds and Their Impact on Fish Health

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The rapid population growth in developing countries has led to strong pressure on capture fisheries. However, capture fisheries have reached their maximal limits of fish production and are supplemented by farmed fish. The growth in aquaculture has led to high demand for fish feeds, which play a very important role in fish nutrition and health. Use of animal protein in fish feeds is expensive; hence, a majority of farmers from developing countries use local feed ingredients from plant origin as a source of dietary protein. However, these ingredients of plant origin provide the best natural substrates for fungi, which can be easily accompanied by mycotoxin development under suitable conditions. The locally made feed comprises ingredients such as maize, oilseeds, and wheat which are mixed together and ground after which the compounded feed is pelleted and stored. Among the ingredients, maize and oilseeds are more susceptible for mycotoxigenic fungi compared to other ingredients. The outcomes of mycotoxin contamination in fish feeds are not different from other animal species intended for human consumption, and they are directly associated with production losses, particularly decreased weight gain and feed conversion, impaired immune system and reproductive performance, and increased fish mortality. Fish may also carry mycotoxin residues along the food chain, thus compromising human health. Hence, it is important to ensure the control of mycotoxin contamination in fish feeds, especially during the production and storage.

1. Introduction

Fish feed is an essential part of the aquaculture industry and comprises 40–50% of the total production cost in intensive culture systems [6]. It also has an important contribution to the production of fish feed since it tends to affect the quality of eggs [7]. A majority of fish farmers in developing countries use locally made fish feeds or commercially imported feeds for Nile tilapia (Oreochromis niloticus) and African catfish (Clarias gariepinus) production. The imported fish feed is more expensive than the locally made ones. Hence, many fish farmers use locally made fish feed usually produced and stored in large quantities in order to reduce production costs and increase profit margins [8]. These ingredients can be ground...
manually and mixed in a hand-operated mixer and then made into pellets using a pelleting machine. Such ingredients are often subjected to contamination by molds during preharvest and/or due to poor storage conditions [10]. Prolonged storage and high temperature and humidity conditions are some of the factors that facilitate fungal development and production of attendant mycotoxins, compromising feed quality that can adversely affect the health of animals and humans [11].

Some molds are capable of producing mycotoxins, and some of these mycotoxins can cause some degree of acute toxicity when given in high amounts and are the potential carcinogens [12]. *Aspergillus*, *Fusarium*, and *Penicillium* are the three most important genera of toxigenic fungi in the tropics [13]. The presence of toxigenic fungi, some producing mycotoxin in farmed fish has increased in recent years owing to the increasing use of plant materials as components for fish feeding [5]. Contamination of fish feeds by mycotoxins and the possible transfer of these toxins into farmed fish and fish-derived products for human consumption remain a serious food safety concern [14].

Around 300–400 mycotoxin types are known to date [15], but the most important in tropical countries are aflatoxins (AFs) (AFB1, B2, G1, and G2) and fumonisins (FBs) (FB1, FB2, and FB3) [16]. In addition to AFs and FBs, ochratoxin A (OTA) and trichothecenes (THs) are also important [17].

Mycotoxin contamination has been implicated with a reduction in fish productivity, anemia, hemorrhaging, liver impairment, weight loss, increased vulnerability to secondary infectious diseases, reduced reproductive capacity, and even mortality [18–21], resulting in serious economic losses [22, 23].

Since aquaculture is a growing sector in a majority of the developing countries, especially in Africa, the aim of this review is to give an overview of fungal and mycotoxic contamination of fish feed, feed ingredients, and their effects on fish health.

### 2. Feed Consumption in Farmed Fish

Fish feed is the major cost item in intensive farming systems, and they represent 50 to 70 percent of fish farmers’ production costs [24]. Requirements for intensive aquaculture are high-quality animal protein, lipid, and other essential nutrients [25]. In order to reduce the feed cost, several efforts have been made to replace the expensive feed ingredients. Incorporating vegetable oil, increasing levels of plant ingredients, and reduction in the level of costly fish meal are appropriate husbandry practices that have been adopted to reduce maintenance costs (particularly feed costs). Zhao et al. [26] reported that fish meal can be completely replaced by soy protein concentrate by increasing feeding frequency for Nile tilapia less than 2 grams. A combination of 76% rice bran and 24% fish meal, which is a mix of dried freshwater shrimp *Caridina* sp., or maize bran, sometimes with the addition of some “dagaa” *Rastrineobola argentea* meal, shows good growth performance on fish [8, 27]. Despite their higher nutritional values, plant ingredients in fish feeds have a higher potential of being contaminated with toxigenic fungi than animal ingredients. This potential is further increased in tropical and subtropical conditions due to storage under humid and hot conditions [28].

### 3. Occurrence of Mycotoxigenic Fungi in Fish Feeds and Ingredients

Fungi are ubiquitous in the environment, being found in water and suitable organic nutrients when appropriate temperature conditions prevail [17]. They have been reported to occur in food and feed worldwide with some of them capable of producing a wide array of mycotoxins. Four major genera stand out: *Alternaria*, *Aspergillus*, *Fusarium*, and *Penicillium* [17]. Among the genus *Aspergillus*, *A. flavus* and *A. parasiticus* are the major aflatoxin producers that are likely harmful to animals or humans [11]. Several *A. flavus* strains may or may not produce either aflatoxin B1 or B2 [11]. Secondary metabolites such as sterigmatocystin, cyclopiazonic acid (CPA), kojic acid, beta-nitropropionic acid, asperitoxin, aflatrem, and aspergillic acid are other toxic compounds also produced by *A. flavus* [11]. *Aspergillus parasiticus* produces aflatoxins G1 and G2, in addition to aflatoxins B1 and B2, but does not produce CPA [11]. *Aspergillus ochraceus* and *A. carbonarius* are the main producers of ochratoxin A (OTA), and they are commonly found in grapes, dried vine fruits, wine, and coffee [29]. However, only a few strains of *A. niger* are capable of producing OTA [30]. *Aspergillus fumigatus* is the main producer of genotoxic and cytotoxic mycotoxins, like gliotoxin [31]. Some other species of *Aspergillus*, such as *A. tamarii* and *A. versicolor*, produce CPA and fumuclavine A and have been responsible for “kodua” poisoning [32]. Kodua is known for poisoning that causes tremors, sleepiness, and giddiness [32, 33].

*Aspergillus* species are ubiquitous in tropical environments and are predominantly isolated in food and feed from the tropics [11]. Fish feeds are frequently contaminated by *Aspergillus* species (Table 1). Several studies performed in tropical countries reported that *A. flavus* and *A. parasiticus* are the major dominant species isolated from fish feed [33, 37, 39, 40]. Fallah et al. [39] and Hassan et al. [44] found that 47.5% and 70% of fish feed from Egypt and Iran, respectively, were contaminated by *A. flavus*. Fish feeds from Brazil and East Africa were contaminated by *A. flavus* at 35% and 54.5%, respectively [35, 40]. *Aspergillus tamarii* were isolated at a frequency of 9.1% and 8% in fish feeds from East Africa and Iran, respectively. *Aspergillus niger* (6%, 13.9%, 36%, and 39.1%) and *A. ochraceus* (10.2%) as the potential ochratoxigenic fungi were isolated from fish feed from East Africa, Iran, Portugal, and Brazil [10, 35, 39, 40]. Other *Aspergillus* species commonly isolated from fish feeds are *A. versicolor*, *A. fumigatus*, *A. candidus*, *A. glaucus*, and *A. oryzae* [35, 37, 39, 40]. Table 1 compares data from previous studies on the most frequently isolated fungi from fish feeds and their ingredients.

*Fusarium* species are destructive pathogens on cereal crops and other commodities and produce some of the most commonly encountered mycotoxins including the trichothecenes and fumonisins in feeds [16]. *Fusarium*...
### Table 1: Frequently isolated fungi from fish feeds and feed ingredients from previous studies.

| Source                                | Country         | Sample size | Common isolates                          | Frequency of isolation (%) | References                  |
|----------------------------------------|-----------------|-------------|------------------------------------------|----------------------------|-----------------------------|
| Tilapia feeds                          | Egypt           | 25          | A. flavus*                               | 48                         | Mohammed et al. [34]        |
|                                        |                 |             | A. niger                                 | 40                         |                             |
|                                        |                 |             | A. fumigatus                             | 8                          |                             |
|                                        |                 |             | A. ochraceus                             | 4                          |                             |
|                                        |                 |             | Penicillium sp., Cladosporium sp., Candida sp., | 40                         |                             |
| Fish feeds and ingredients             | East Africa     | 52          | A. flavus*                               | 54.5                       | Marijani et al. [35]        |
|                                        |                 |             | A. tamarii                               | 9.1                        |                             |
|                                        |                 |             | Mucor sp.                                | 6.1                        |                             |
|                                        |                 |             | Phoma sp.                                | 6                          |                             |
|                                        |                 |             | A. niger                                 | 3                          |                             |
|                                        |                 |             | E. rubrum                                | 3                          |                             |
|                                        |                 |             | P. chrysogenum                           | 3                          |                             |
| Commercial and formulated fish feeds   | Kenya           | 121         | Aspergillus sp.                          | 50.5                       | Njagi [36]                  |
|                                        |                 |             | Mucor sp.                                | 56                         |                             |
|                                        |                 |             | Rhizopus sp.                             | 49.5                       |                             |
|                                        |                 |             | Saprolegnia sp.                          | 42.5                       |                             |
|                                        |                 |             | Penicillium sp.                          | 31                         |                             |
| Fish feeds and ingredients             | Brazil          | 54          | Penicillium sp.*                         | 83.3                       | Gonçalves-Nunes et al. [37] |
|                                        |                 |             | Aspergillus sp.                          | 66.7                       |                             |
|                                        |                 |             | Rhizopus sp.                             | 23.3                       |                             |
|                                        |                 |             | Cladosporium sp.                         | 20                         |                             |
| Rainbow trout feed                     | Argentina       | 28          | Cladosporium cladosporioides*            | 53.6                       | Greco et al. [38]           |
|                                        |                 |             | Eurotium repens                          | 21.4                       |                             |
|                                        |                 |             | Eurotium rubrum                          | 14.3                       |                             |
|                                        |                 |             | Mucor sp.                                | 7.1                        |                             |
|                                        |                 |             | A. versicolor                            | 3.6                        |                             |
|                                        |                 |             | P. crustosum                             | 3.6                        |                             |
|                                        |                 |             | P. expansum                              | 3.6                        |                             |
|                                        |                 |             | P. chrysogenum                           | 3.6                        |                             |
| Fish feeds                             | Iran            | 86          | A. flavus*                               | 47.3                       | Fallah et al. [39]          |
|                                        |                 |             | A. parasiticus*                          | 16.1                       |                             |
|                                        |                 |             | A. niger                                 | 13.9                       |                             |
|                                        |                 |             | A. ochraceus                             | 10.2                       |                             |
|                                        |                 |             | A. fumigates                             | 9                          |                             |
|                                        |                 |             | A. versicolor                            | <5                        |                             |
|                                        |                 |             | A. carbonarius                           | <5                        |                             |
|                                        |                 |             | A. nomius                                | <5                        |                             |
|                                        |                 |             | A. ustus                                 | <5                        |                             |
|                                        |                 |             | Fusarium sp.                             | 26.2                       |                             |
|                                        |                 |             | Eurotium sp.                             | 10                         |                             |
|                                        |                 |             | Penicillium sp.                          | 41.5                       |                             |
|                                        |                 |             | Mucor sp.                                | <10                        |                             |
|                                        |                 |             | Cladosporium sp.                         | <5                        |                             |
|                                        |                 |             | Alternaria sp.                           | <5                        |                             |
| Fish feed                              | Brazil          | 60          | Cladosporium sp.*                        | 85                         | Barbosa et al. [40]         |
|                                        |                 |             | P. citrinum*                             | 71                         |                             |
|                                        |                 |             | A. flavu                                 | 35                         |                             |
|                                        |                 |             | A. niger                                 | 36                         |                             |
|                                        |                 |             | Eurotium sp.                             | 20                         |                             |
|                                        |                 |             | Wallemia                                 | 40                         |                             |
|                                        |                 |             | Aureobasidium                            | 10                         |                             |
|                                        |                 |             | Mucor, and                               | 10                         |                             |
|                                        |                 |             | Nigrospora sp.                           | <10                        |                             |
verticillioides is ubiquitous in maize and produces FBs, which are generally more prevalent when crops are under drought stress or suffer excessive insect damage [45]. Fusarium graminearum is the main producer of the deoxynivalenol (DON) and estrogenic compound zearalenone (ZEN) [46]. F. graminearum is pathogenic on maize, wheat, and barley and produces these toxins whenever it infects the grains before harvest.

Aspergillus niger also produces FBs, and several commodities may be affected [30]. The most common fungi associated with maize which is the common ingredient in fish feeds are F. verticillioides and F. proliferatum. A study on the infections of Fusarium sp. in feed ingredients was done by Ivić et al. [47] and found that the dominant species were 27% of F. graminearum isolated on wheat, 83% of F. verticillioides isolated on maize, and 34% of F. sporotrichioides isolated on soybean. The authors of this study concluded that the risk of contamination with Fusarium toxins is higher for maize and wheat than for soybean. Fusarium species appear to be uncommon to fish feeds as they were isolated in a very small percentage but may cause adverse effects to fish [10, 37, 39, 42].

Some Penicillium species are mycotoxin producers and can negatively affect the health of humans and animals [48]. Penicillium verrucosum produces OTA but occurs only in cool temperate climates, where it infects small grains like wheat and barley [48] and not commonly isolated in tropical areas. Penicillium citrinum is a species where citrinin toxin was first isolated, but the toxin has subsequently been identified to be produced by several Penicillium and Aspergillus species [49]. No information is available on the contamination of citrinin in fish feeds; however, its producer P. citrinum has been isolated from fish feeds [37, 40]. Penicillium expansum, Aspergillus, Penicillium, and Paecilomyces fungal species produce patulin, whereas ergot alkaloids are compounds produced as a toxic mixture of alkaloids in the sclerotia of the species of Claviceps [50]. Penicillium expansum is particularly linked with a range of moldy fruits and vegetables, especially in rotting apples and figs while the species of Claviceps are common pathogens of several grass species. Penicillium expansum occurs best in wet, cool (<25°C) environments, and the growth rate was the fastest at a relative humidity of 90% [50]. Penicillium

### Table 1: Continued.

| Source         | Country  | Sample size | Common isolates                        | Frequency of isolation (%) | References               |
|----------------|----------|-------------|----------------------------------------|---------------------------|--------------------------|
| Fish feeds     | Brazil   | 36          | A. flavus*, A. fumigates, A. terreus, A. candidus, A. oryzae, A. penicillioides, Eurotium sp., Penicillium sp., Cladosporium sp., Fusarium sp. | 60.47                     | Filho et al. [41]         |
| Tilapia feed   | Mexico   | 30          | Aspergillus flavus*                   | 6.7                       | Rodriguez-Cervantes et al. [42] |
| Sea bass feeds | Portugal | 87          | A. flavus*, A. niger, A. ochraceus, A. fumigates, A. clavatus, Penicillium sp., Absidia sp., Mucor sp., Alternaria sp. | 60.66                     | Almeida et al. [10]       |
| Rainbow trout feed | Iran   |             | A. flavus*, A. niger, A. ochraceus, A. fumigates, A. clavatus, Penicillium sp., Absidia sp., Mucor sp., Alternaria sp. | 60.0                       | Alinezhad et al. [43]     |
| Fish feeds     | Egypt    | 50          | A. flavus*, A. niger, A. ochraceus, A. candidus, Penicillium sp., Mucor sp., Cladosporium sp., Rhizopus sp. | 56.0                       | Hassan et al. [44]        |

*The most commonly isolated species.
expansum has been isolated in fish feeds, and the use of vegetables as feed ingredients could be the reason for the presence of this species in the finished fish feeds [38].

Penicillium crustosum and P. commune are closely related and contain CPA and roquefortine C (ROQ-C) [35, 38]. Other Penicillium species which are isolated in fish feeds are Penicillium glabrum, P. nalgiovense, P. corylophilum, P. implicatum, and P. restrictum [37, 38, 41].

The genus Eurotium is also an important mycotoxin producer and grow exceptionally well at low water activities [52]. Most of the Eurotium species are of special interest to feed mycology due to their xerophilic physiology; many isolates are able to grow at water activities below 0.75, and some isolates are able to grow at values as low as 0.64 aw [53]. Eurotium amstelodami, E. repens, and E. rubrum reported to produce aflatoxin [23, 38], and ochratoxin A is produced by E. amstelodami [23]. Although most of the studies on fish feed mycobiota have been concentrated on the presence of mycotoxigenic genera Aspergillus, Fusarium, and Penicillium, Eurotium sp. have as well reported as frequent contaminants [38, 39, 41]. Commonly, Eurotium species isolated from fish feeds are E. repens and E. rubrum [35, 38]. Eurotium rubrum were isolated with a frequency of 25% and 3%, while E. repens (21.4%) were isolated from fish feed from East Africa and Argentina. Since some of the Eurotium species produce aflatoxin and OTA, their presence in fish feeds could affect fish health and cause serious economic losses.

The commonly used raw ingredients in the manufacturing of fish feeds are maize, rice, wheat bran, soybean, sunflower seed cake, and cottonseed cake, which are highly susceptible to mycotoxin-producing fungi [17, 54, 55]. Several mycotoxigenic fungi had been isolated from ingredients used for fish feed from different fish farms around the world [28, 35, 36]. The presence of these mycotoxigenic fungi in the ingredients might also cause the formation of mycotoxin in the finished fish feeds [35, 38, 40].

Aspergillus flavus was the dominant fungal species isolated from maize bran, cottonseed cake, sunflower oil seed cake, and cassava; however, soybean samples were the least contaminated by mycotoxigenic fungi [35]. In another survey conducted in Brazil, soybean bran intended for fish feeds were contaminated by A. flavus (61.5%), P. citrinum (81.8%), and A. parasiticus (7.7%) [37]. Aspergillus flavus was the dominant species isolated from maize bran (50%), and other cereals (66.6%) were designated for fish feed from Brazil. Other fungal species isolated at higher frequencies from maize bran and other cereals were P. citrinum (50% and 90.9%) and A. parasiticus (16.7%), respectively [37].

Factors like high temperature and relative humidity, together with inappropriate handling and storage practices increase the likelihood of the growth of mycotoxigenic fungi. In addition, storage practices in most developing countries are poor, which make them more vulnerable to fungal contamination [56]. Also, insect infestation can cause heating and generation of moisture. For the cereal grain, an increase in temperature is expected due to respiration, which may likewise occur due to insect or fungal activity. Heating results in moisture condensation in cool areas inside the grain mass [57]. As a result of this, further fungal growth and insect infestation are encouraged. Normally, the standard moisture content required for most cereals often used as feed ingredients should be 14% before storage [58]. Therefore, it is very important to utilize feed ingredients which have moisture content at or below the safe level of 13% [58]. Aeration with cool air may also help to prevent the stored ingredients against fungal development [59].

4. Mycotoxin Contamination in Fish Feed and Feed Ingredients

Plant proteins such as oilseeds are excellent alternatives to animal proteins in fish feeds because they are less expensive and are more abundant in many parts of the world [5]. Diets for Nile tilapia and warm water species such as carp and channel catfish are predominantly formulated using high amounts of grains and plant proteins, and as such, the feeds are at high risk to contamination by mycotoxins [60]. Cereals are common ingredients used in fish feeds and like the oilseeds, they are the main point of entry for many mycotoxins in humans and fish dietary systems, particularly in Africa [35]. Bran, which is also a common ingredient in fish feed, is usually derived from any cereal grains such as rice, maize, wheat, oats, barley, rye, and millet during the dry milling process [61]. Unfortunately, this dry milling is not likely to destroy mycotoxins. Mycotoxins are generally concentrated in the bran and outer layers of grains but are less in the endosperm [62]. This suggests that bran or wholemeal grains have the potential to contain higher concentrations of certain mycotoxins than those manufactured from flours or grits milled from the grain endosperm [61]. The use of mycotoxin contaminated bran and other ingredients provide an avenue for the finished fish feed to contain similar mycotoxins posing a health hazard in fish.

4.1. Occurrence of Aflatoxin. The incidences of aflatoxin contamination in fish feed have been reported in many countries of the world especially in the tropical and subtropical regions as shown in Table 2. Therefore, this means fish feed in both tropical and subtropical regions are more prone to aflatoxin contamination compared to the temperate regions [68]. The recommended regulatory limit for aflatoxin in fish feeds is 20 μg·kg\(^{-1}\) [66], but a majority of samples from tropical countries are above this limit [35, 39, 40].

In the study of Marijani et al. [35], levels of mycotoxins in fish feeds and feed ingredients from fish farms, imported fish feeds, and feeds made by local feed millers in East Africa were analyzed. Results obtained revealed that aflatoxin contamination was higher in feed processed at farm level in terms of incidence rate (64.3%), feed ingredients (50%), and local commercial feed mills (35.7%), but not in imported feed. Inclusion of antifungal agents in imported feeds to prevent fungal growth during prolonged and varied storage conditions in farms might be a possible reason for the
absence of aflatoxin in imported feed samples [35]. In the same study, fish feed samples from Kenya were found to be highly contaminated with aflatoxin at concentrations ranging from <2–806.9 μg·kg⁻¹, followed by those from Tanzania (<2–377.9 μg·kg⁻¹), Uganda (<2–28.0 μg·kg⁻¹), and Rwanda (<2–4.8 μg·kg⁻¹). In another study from Kenya, eighty-four percent of fish feed samples were tested positive for aflatoxins, ranging from 1.8 to 39.7 μg·kg⁻¹ [65]. Other studies from tropical countries, such as Brazil [39], Iran [40], and Egypt [44], reported that fish feeds were contaminated by aflatoxin at a concentration ranging from 1.83–67.35 μg·kg⁻¹, 0.46–68.5 μg·kg⁻¹, and 52.5–150 μg·kg⁻¹, respectively. In another study from Egypt, around 42.86% of fish feed were contaminated with aflatoxins at a value higher than the permissible limit of 20 μg·kg⁻¹ [69].

Alinezhad et al. [43] observed that pellets of rainbow trout feed and feed ingredients from Iran were contaminated with aflatoxins in the range of 1.83 to 67.35 μg·kg⁻¹. Altug and Beklevik [70] reported aflatoxin contamination in 56% of commercial fish feeds in Turkey at levels of over 21 μg·kg⁻¹. Hassan et al. [44] studied the mycological quality of fish feed from Egypt and detected aflatoxin at significantly higher levels at mean levels of 105.2 ± 1.3 μg·kg⁻¹ in 40% of samples.

Gonçalves-Nunes et al. [37] screened raw materials and finished fish feeds for aflatoxin contamination in Brazil. Aflatoxin B₁ was detected in the mean level of 1.1 μg·kg⁻¹, 7.4 μg·kg⁻¹, and 3.8 μg·kg⁻¹ in maize bran, other cereal products, and finished fish feed, respectively. Another fish feed survey conducted in Brazil by Hashimoto et al. [71] detected aflatoxin at maximum contamination levels of 15.6 μg·kg⁻¹. In addition, a survey on commercial shrimp feeds conducted in the Philippines found AFB₁ contamination levels up to 120 μg·kg⁻¹ [69].

Aflatoxin contamination of cottonseed cake has been a major concern worldwide as extremely high contents ranging between 200 and 300 mg·kg⁻¹ were reported in samples exported from the USA to the European markets [72]. In a survey done by Rodriguez et al. [73] on contamination of aflatoxins in feeds and their ingredients in the Middle East and Africa, it was found out that sunflower meal has the highest contamination level in the whole survey (556 μg·kg⁻¹). A survey done in East Africa by Marijani et al. [35] found that cottonseed cake intended for fish feeds was contaminated by aflatoxin with a maximum concentration of 377.9 μg·kg⁻¹, while soybeans were not contaminated. Sunflower seed cake was the only ingredient that contained the highest AFB₁ concentration of 806.9 μg·kg⁻¹ when compared to maize bran, soybeans, cottonseed cake, and rice bran [35]. In another survey from Tanzania conducted by Mmongoyo et al. [74], sunflower seed cake was contaminated with aflatoxin with a maximum concentration of

### Table 2: Mycotoxin levels (μg·kg⁻¹) in fish feed from developing countries.

| Source             | Country   | Sample size | AF  | FB  | DON | OTA | NIV | AOH | T-2 | ZEN | PL %⁺ | Reference          |
|--------------------|-----------|-------------|-----|-----|-----|-----|-----|-----|-----|-----|------|-------------------|
| Tilapia feeds      | Egypt     | 25          | <LOD| na  | na  | na  | na  | na  | na  | na  | 0    | Mohamed et al. [34]|
| Fish feeds         | East Africa | 52         | 126 | 755.4 | 2834.6 | nd  | 732.5 | 91.3 | <LOD | na   | 48 (AF), 0 (FB), 0 (DON) | Marjiani et al. [35]|
| Abalone feeds      | South Africa | 0.98       | 424 | 100 | 0.259 | 100 | na  | na  | na  | na  | 0    | Laubscher [63]       |
| Tilapia feeds      | Mexico    | 30          | <LOD| 2587 | na  | na  | na  | na  | na  | na  | 0    | Rodríguez-Cervantes et al. [42]|
| Rainbow trout      | Argentina | 28          | 2.82***<LOD | 230** | 5.26** | na  | na  | na  | 70.08*** | 87.97*** | 0 | Greco et al. [38] |
| Fish feeds         | Iran      | 86          | 68.5 | na  | na  | na  | na  | na  | na  | na  | 0    | Fallah et al. [39] |
| Fish feeds         | Brazil    | 60          | <LOD| 4.94 | na  | <LOD | na  | na  | na  | na  | 0    | Barbosa et al. [40]  |
| Fish feeds         | Central Europe | na         | na  | na  | 825 | na  | na  | na  | na  | 511 | 0    | Pietsch et al. [64]  |
| Fish feeds         | Egypt     | 50          | 150 | na  | na  | na  | na  | na  | na  | na  | 0    | Hassan et al. [44]   |
| Fish feeds         | Brazil    | 54          | 3.8*** | 2587 | na  | na  | na  | na  | na  | na  | 0    | Gonçalves-Nunes et al. [37]|
| Sea bass feeds     | Portugal  | 87          | nd  | na  | na  | na  | na  | na  | na  | na  | 0    | Almeida et al. [10]  |
| Rainbow trout      | Iran      | 67.35       | na  | na  | na  | na  | na  | na  | na  | na  | nm   | Alinezhad et al. [43] |
| Fish feeds         | Kenya     | 81          | 39.7 | na  | na  | na  | na  | na  | na  | na  | 13.5 | Mwihiia et al. [65]  |

*Maximum level of mycotoxin content in positive samples; **median of positive samples excluding results of estimated concentrations; ***mean level of mycotoxin content in positive samples; *percentage of samples that are above the permissible limit (PL) of AFs, FBs, and DON in feeds recommended by FDA [66] and EU [67]; nd, not detected; na, not analyzed in the study; nm, not mentioned in the study.
662.7 μg·kg⁻¹ recorded. Interventions to control aflatoxin contamination along the oilseed product value chain should be implemented to enhance feed safety in African countries.

Looking at the data in Table 2, it can be confirmed that the occurrence of aflatoxin is very high from fish feeds from Africa. This is worrying as the high incidences of aflatoxicosis in human were also reported in Africa [75]. During human aflatoxicosis outbreaks in 2005 and 2006, maize were heavily contaminated with aflatoxin with maximum levels of 48,000 and 24,000 μg·kg⁻¹, respectively [75]. Daniel et al. [75] concluded that drought and famines followed by unseasonable rains during harvest and improper storage of homegrown maize in moist conditions were the reasons behind the high incidence of aflatoxicosis.

Maize intended for fish feeds was contaminated by AFB₁ at a maximum concentration of 135 μg·kg⁻¹ [35]. Similar results were also reported by Reddy and Salleh [76], who found out that 22.5% of samples of maize had AFB₁ contamination ranging from 20.6 to 135 μg·kg⁻¹. The poorest quality maize is used for animal feeding, which makes animals more at risk to aflatoxicosis [45].

Rice is another important staple food in Africa and Asia and its bran is widely used for animal feeding [77]. Rice bran intended for fish feed from East Africa were not contaminated by aflatoxin [35]. In another study from Iran, rice bran was contaminated by aflatoxin with the mean concentration of 18 μg·kg⁻¹ [78]. Wheat does not grow well in tropical climates; however, its bran is widely used as a component of animal and fish feeds [28, 79]. Another cereal which is used in fish feed as an ingredient is sorghum. The incidence of aflatoxin in sorghum and millet from northern Nigeria was investigated by Apen Daneil et al. [80], and they found out that 28.6% sorghum (0.96–21.74 μg·kg⁻¹) and millet grain (105–149.6 μg·kg⁻¹) were contaminated with aflatoxin. Out of 52 ingredients intended for fish feed from East Africa, sorghum and wheat bran were detected at a very low concentration of less than 3 μg·kg⁻¹ [35, 81]. Another study from Brazil reported that out of 140 sorghum collected, only 12.8% were contaminated by aflatoxin [82]. Shetty and Bhat [83] found out that 20% of normal sorghum and 89% of normal maize samples also contained aflatoxin B₁. Bandypadhyay et al. [84] suggested that if the primary cereal is sorghum instead of maize, then the risk of aflatoxin-related problems is reduced by 4-fold. Low level of aflatoxin contamination in wheat bran, sorghum, and soybean suggests that they are likely to be useful in the formulation of fish feeds with aflatoxin below levels that could elicit any adverse complications on fish health.

4.2. Occurrence of Fusarium Mycotoxins. There are several reports on the contamination of cereal grains and animal feed with *Fusarium* mycotoxins worldwide [17, 79]. The most important among them are the trichothecenes, ZEN, and the fumonisins [85]. The trichothecenes are subdivided into four basic groups, with types A and B being the most important. Type A trichothecenes include T-2 toxin, HT-2 toxin, neosolaniol, and diacetoxyscirpenol (DAS) [85]. Type B trichothecenes include DON also known as vomitoxin, nivalenol (NIV), and fumaronal-X. Fumonisins, particularly FB₁ and FB₂, are found in maize grain which is a major component of feeds for warm water fish [86]. Contamination of fumonisins in cereals is dependent on the geographical region, season, and conditions under which the particular cereal is grown, harvested, and stored [45]. The prevalence of fumonisins has been reported to be 100% or close to it in all surveillance studies on maize from different parts of Africa [13]. Several studies have shown that maize bran which is mainly used for animal/fish feed has been contaminated with FBs [21, 79]. Fumonisin was detected at the concentration of 1 mg·kg⁻¹ on the maize bran used for animal feed from Tanzania [87]. The prevalence of *F. verticillioides* and production of FB₁ in cereal grains and oilseeds in Zimbabwe was established by Gamanya [88]. While the authors did not find *Fusarium* and FB₁ contamination in sunflower and soybean samples tested, high incidences were recorded for maize followed by wheat and sorghum [88]. Maize bran and soybeans from East Africa used for fish feeds contained a maximum of up to 3970.1 μg·kg⁻¹ and 1402.3 μg·kg⁻¹ of FB₁, respectively, while cottonseed cake, sunflower seed cake, and rice bran were not contaminated with FB₁ [35]. This suggests that maize is more susceptible to FBs when compared to other feed ingredients. In the same study, they found out that fish feeds processed at the farm level contained a maximum FBs concentration of 2834.6 μg·kg⁻¹ [35], and samples tested were below the regulatory limits of 5000 μg·kg⁻¹ recommended by EU [67].

DON is the most often occurring trichothecene and is prevalent in crops used for food and feed production, generally found in various cereal crops such as wheat, barley, oats, rye, rice, and maize [85]. Natural occurrence of DON in cereals is certainly prevalent, and surveys from South America, Canada, China, and many countries of Europe have shown contamination levels in excess of 50% in oats, barley, and wheat with mean concentrations as high as 9 mg·kg⁻¹ in barley [46]. In a survey carried out between 2004 and 2007, DON was the predominant mycotoxin with highest levels detected in wheat bran [89]. Few studies have been carried out on the contamination of DON in finished fish feeds [86]. A survey done in Central Europe has shown that more than 80% of the samples from commercial fish feed were contaminated with DON with a mean concentration of 289 μg·kg⁻¹ recorded [64]. Fish feed processed at farm level were contaminated with the mean DON concentration of 755 μg·kg⁻¹ while among the ingredients, maize bran was highly contaminated with 984 μg·kg⁻¹ [35]. Another study from Nigeria found out that fish feeds were contaminated with a mean DON concentration of 85.9 μg·kg⁻¹ [90]. All fish feeds from these studies were below the regulatory limits of 5000 μg·kg⁻¹ recommended by EU [67]. Sixty-eight samples of shrimp and fish feed from Asia and Europe were contaminated with DON at a mean concentration of 162 μg·kg⁻¹ and maximum level of 413 μg·kg⁻¹ [91].

Zearalenone, a toxic metabolite of *Fusarium* fungi is commonly found as contaminant in maize, and also it may occur in oats, barley, wheat, and sorghum [92]. However, the production of ZEN is favored by high humidity and low temperature conditions [93]. It may co-occur with DON in
grains such as wheat, barley, oats, and maize and FBs in maize [92]. ZEN was found in fish feed from Asia with average concentrations of 76.2 μg·kg⁻¹ [28]. Other studies from Europe reported that fish feeds were contaminated with ZEN with a maximum concentration of 511 μg·kg⁻¹ [64]. However, the ZEN values found in these studies do not exceed the values (5000 μg·kg⁻¹) currently recommended by the European Commission in animal feeds [67]. DON and ZEN in unprocessed cereals and soybean were detected at the mean concentrations of 1.461 ± 2.265 μg·kg⁻¹ and 656 ± 853 μg·kg⁻¹, respectively, in samples collected in 2014, while in 2015 these means were 2.687 ± 2.731 μg·kg⁻¹ and 1,140 ± 1,630 μg·kg⁻¹, respectively [94]. The authors suggested that higher contamination determined during 2015 could be explained by high to extreme humidity evidenced in the period of cereals’ growth and harvesting. The occurrence of DON and FBs in fish feeds, even at low levels, may be of concern, since it can cause growth retardation and immunotoxic effects in fish [95]. These results suggest that ZEN contamination may pose little health risk (if any) to the consumers of the fish [96].

4.3. Other Mycotoxins. Other mycotoxins like OTA, NIV, DAS, T-2 toxin, alternariol (AOH), and ROQ-C have been reported to occur in fish feeds and ingredients intended for fish feed formulation [35]. Cottonseed cake for fish feed formulation was the only ingredient contaminated by OTA with a maximum concentration of 24.2 μg·kg⁻¹ [35]. Nivalenol was detected in fish feeds processed at farm level with a maximum concentration of 732.5 μg·kg⁻¹, while no ingredients intended for fish feeding was contaminated by NIV. Other mycotoxins like DAS, T-2, and ROQ-C were detected in fish feeds and their ingredients but at very low concentrations [35].

Also, an immunosuppressive mycotoxin, gliotoxin, was detected in oilseed cakes at levels up to 45 μg·kg⁻¹, which was associated with the presence of toxigenic isolates of A. fumigatus [97].

5. Effects of Mycotoxin on Fish Health

The toxic effects of mycotoxins are not only depended on the dose in feeds but as well as on the duration of toxin exposure, species, as well as the sex and age of the animal [94].

Among the mycotoxins, AFB1 is the most studied in fish, possibly because of its natural occurrence being most widely found in tropical countries and that it is a known human carcinogen and most potent hepatotoxin [98]. These studies on toxicity effect of AFB1 on farmed aquatic species include rainbow trout, [23, 99, 100]; Nile tilapia, [14, 19, 101–104]; channel catfish, [22, 105]; rohu, [106, 107]; sea bass, [98]; gibel carp, [18]; beluga, [108]; and abalone [63].

Considering the results of the studies in Table 3, the biological effects of AFB1 in these aquatic species depend on the toxin’s concentration in feed and species. Channel catfish, Ictalurus punctatus, appears to be one of the most resistant among fish species when exposed to AFB1, while rainbow trout is the most sensitive to AFB1, and exposing them at concentrations as low as 0.4 μg AFB1 kg⁻¹ may cause a 14% chance of developing tumors [22, 99]. Previously, there are no studies on hepatocellular carcinomas in channel fish caused by AFB1, but there are reports that dosing them with higher concentrations of AFB1 resulted in decreased growth rate and moderate internal lesions [22]. European sea bass is also sensitive to AFB1; El-Sayed and Khalil [98] found that exposing them for 4 days with median lethal concentration (LC50) of 180 μg·kg⁻¹ AFB1 causes aflatoxicosis. Other studies on fish have shown reduced growth rates particularly on Nile tilapia and channel catfish-fish diets containing 1880 and 10000 μg AFB1·kg⁻¹ feed, respectively [14, 17, 22]. The mortality rate of 17% was reported in Nile tilapia fed diets containing 2000 μg AFB1·kg⁻¹ [101]. Aflatoxin is also known to affect eye opacity resulting in cataract and blindness, yellowing of the body surface, wounds on the body surface, fin and tail rot, abnormal swimming, feebile and stationary movements, and reduced appetite in tilapia-fed aflatoxin-contaminated diet [19].

Aflatoxin has been reported to disrupt the reproductive system in both male and female animals; however, very few studies had been reported in aquatic animals [116]. The few existing studies show a significant decrease in ovary weight, fecundity, and egg size of gibel carp fed on AFB1-treated ration [18]. In Nile tilapia, a negative effect on gonadosomatic index, fecundity, sperm count, sperm activity, and serum estradiol-17β concentrations was observed after feeding them with 1 and 3 mg·kg⁻¹ AFB1 contaminated for 3 months [117].

The contamination values of AFs found in fish feeds and their ingredients from Africa were high (Table 2) and, as shown in Table 3, can negatively affect farmed fish, thus leading to economic loss to fish farmers.

Fusarium mycotoxins are able to induce both acute and chronic toxic effects. Previous studies have shown that these effects depend on the dose, duration of exposure, and fish species that are exposed (Table 4). Rainbow trout are sensitive to DON when exposed at low dose, while channel catfish are much less responsive (Table 4). Hooft et al. [100] reported that feeding rainbow trout with low, graded levels of DON ranging from 3.0 × 10⁻⁴ to 2.6 × 10⁻² mg·kg⁻¹ from naturally contaminated maize resulted in highly significant decrease in growth, feed intake, feed efficiency, and protein and energy utilization, whereas channel catfish-fed diets containing up to 10 mg·kg⁻¹ DON from either a purified source or naturally contaminated wheat had no effect on the feed consumption, growth, hematocrit values, or liver weight [119]. Also, the rainbow trout liver is sensitive to FB1, because it induces changes in sphingolipid metabolism [131] and is a cancer promoter in this species [123]. Growth performance of Nile tilapia fingerlings was negatively affected when fed with both moniliformin (MON) and FB1 at 70 and 40 mg·kg⁻¹, respectively. However, when compared to channel catfish, Nile tilapia appears to be more resistant to these two mycotoxins as no mortality and histopathological lesions have been reported [102].

Reduction in growth, feed efficiency, and feed intake in fish fed with DON-contaminated diet was reported by Tola et al. [95], Hooft et al. [100], and Döll et al. [118]; however,
| Mycotoxin | Species                     | Exposure dose | Administration | Duration of exposure (weeks) | Toxicity effect                                                                 | References                           |
|-----------|-----------------------------|---------------|----------------|-----------------------------|--------------------------------------------------------------------------------|--------------------------------------|
| Aflatoxin | Nile tilapia (Oreochromis niloticus) | 100 μg AFB₁/kg | Feed: oral     | 10                          | Reduced the growth                                                            | El-Banna et al. [101]                |
|           | Nile tilapia                | 200 μg AFB₁/kg | Feed: oral     | 10                          | Mortality (16.7%)                                                            | El-Banna et al. [101]                |
|           | Nile tilapia                | 5–38.62 μg AFB₁/kg | Feed: oral | 10                          | Survival rate reduced by up to 67%                                           | Cagauan and Tayaban [19]             |
|           | Nile tilapia                | 29 μg AFB₁/kg  | Feed: oral     | 10                          | Yellowing of the body surface Total erythrocyte count, total leucocyte count, and hemoglobin count decreased; weight gain lowest and reduction in the rate survival rate | Cagauan and Tayaban [19]             |
|           | Tilapia                     | 200 ppb AFB₁/kg | Feed: oral     | 10                          | Yellowing of the body surface                                               | Selim et al. [104]                   |
|           | Tilapia                     | 793 and 1641 μg AFB₁/kg | Feed: oral | 5                           | Yellowing of the body surface                                                | Deng et al. [103]                    |
|           | Tilapia                     | 793 and 1641 μg AFB₁/kg | Feed—oral | 15                          | Darkening of body surface                                                    | Deng et al. [103]                    |
|           | Tilapia                     | 2.5 mg AFB₁/kg  | Feed: oral     | 20                          | Affect the hematocrit and growth performance                                | Tuan et al. [109]                    |
|           | Tilapia                     | 2.5 mg AFB₁/kg  | Feed: oral     | 20                          | Feed efficiency rate decreased                                              | Deng et al. [103]                    |
|           | Tilapia                     | 245 μg AFB₁/kg  | Feed: oral     | 20                          | Weight gain lowest                                                           | Deng et al. [103]                    |
|           | Tilapia                     | 245, 638, 793 and 1641 μg AFB₁/kg | Feed: oral | 20                          | Decreased leukocyte count, increased haematopoietic activity of blood-forming tissues | Jantaroai and Lovell [22]             |
|           | Channel catfish (Ictalurus punctatus) | 10000 μg AFB₁/kg | Feed: oral     | 10                          | Reduction in production of oxygen radicals by neutrophils                    | Sahoo and Mukherjee [110]            |
|           | Rohu (Labeo rohita)         | 2.50 and 5.00 mg·kg⁻¹ | Intraperitoneal (i.p.) | 10                          | Reduction of total protein and globulin levels                               | Sahoo and Mukherjee [110]            |
|           | Rohu                        | 1.25; 2.50 and 5.00 mg·kg⁻¹ | Intraperitoneal (i.p.) | 10                          | Total erythrocyte count, total leucocyte count, hemoglobin count, and nitroblue tetrazolium decreased | Mohapatra et al. [107]               |
|           | Rohu                        | 10, 20 and 40 mg·kg⁻¹ | Feed: oral     | 8                           | Reduction in production of oxygen radicals by neutrophils                    | Sahoo and Mukherjee [110]            |
|           | Aflatoxin                   | 20, and 2000 μg AFB₁ kg⁻¹ | Feed: oral     | 24                          | Reduction of total protein and globulin levels                               | Sahoo and Mukherjee [110]            |
|           | Gibel carp (Carassius auratus gibelio) | 1190 μg·kg⁻¹ | Feed: oral     | 3                           | Mortality                                                                      | Nomura et al. [99]                   |
|           | Juvenile rainbow trout      | 0.18 mg·kg⁻¹  | Feed: oral     | 4 days                      | Loss of equilibrium, rapid opercular movement, and hemorrhages of the dorsal skin surface *ALT, AST, and ALP enzymes increased; total protein; Albumin; and Globulin increased | El-Sayed and Khalil [98]             |
|           | Sea bass (Dicentrarchus labrax L.) | 0.018 mg·kg⁻¹ | Feed: oral     | 6                           | Mortality                                                                      | Nomura et al. [99]                   |

*ALT, AST, and ALP enzymes increased; total protein; Albumin; and Globulin increased
Table 3: Continued.

| Mycotoxin | Species                  | Exposure dose | Administration | Duration of exposure (weeks) | Toxicity effect                                                                 | References                  |
|-----------|--------------------------|---------------|----------------|-----------------------------|--------------------------------------------------------------------------------|-----------------------------|
| OTA       | Channel catfish          | 1.0, 2.0, 4.0, or 8.0 mg·kg\(^{-1}\) | Feed: oral     | 8                           | Reductions in body weight gain                                                 | Manning et al. [111]         |
| OTA       | Channel catfish          | 4.0, or 8.0 mg·kg\(^{-1}\) | Feed: oral     | 8                           | Feed conversion ratio was significantly poorer                                 | Manning et al. [111]         |
| OTA       | Channel catfish          | 8.0 mg·kg\(^{-1}\) | Feed: oral     | 8                           | Hematocrit was significantly lower                                              | Manning et al. [111]         |
| OTA       | Juvenile common carp     | 4.0 mg·kg\(^{-1}\) | Feed: oral     | 6                           | Mortality (80.49%)                                                            | Manning et al. [112]         |
| OTA       | Black tiger shrimp       | 1000 μg·kg\(^{-1}\) | Feed: oral     | 8                           | No negative impact in shrimp                                                   | Supamattaya et al. [113]     |
| Stg       | Nile tilapia             | 5, 10 and 50 μg·ml\(^{-1}\) | Intragastric   | 4                           | Clastogenic, decrease of body weight, and the increase in frequencies of micronucleated red blood cells (MN RBC) and chromosomal aberrations in the kidney | Abdel-Walihab et al. [114]   |
| Stg       | Nile tilapia             | 1.6 μg·kg\(^{-1}\) bwt Corn oil: oral | 4             | Genotoxic and toxicopathological effects                                        | Mahrous et al. [115]         |

*ALT: alanine aminotransferase; ALP: alkaline phosphatase; AST: aspartate transaminase.

Table 4: Toxic effects of *Fusarium* mycotoxins in different species of fish.

| Mycotoxin | Species                  | Exposure dose | Administration | Duration of exposure (weeks) | Toxicity effect                                                                 | References                  |
|-----------|--------------------------|---------------|----------------|-----------------------------|--------------------------------------------------------------------------------|-----------------------------|
| DON       | Rainbow trout *Oncorhynchus mykiss* | 2.6 mg·kg\(^{-1}\) | Feed: oral     | 8                           | Decrease in growth, feed intake, feed efficiency, and protein and energy utilization. | Hooft et al. [100]          |
| DON       | Atlantic salmon *Salmo salar* L. | 3.7 × 10\(^{-3}\) mg·kg\(^{-1}\) | Feed: oral     | 8                           | Reduction in feed intake and decrease in specific growth rate                  | Döll et al. [118]           |
| DON       | Channel catfish *Ictalurus punctatus* | 5.0–10.0 mg·kg\(^{-1}\) | Feed: oral     | 8                           | Mortality                                                                      | Manning et al. [119]        |
| T-2 toxin | Juvenile channel catfish | 1.25, 2.5, and 5.0 mg·kg\(^{-1}\) | Feed: oral     | 8                           | Reductions in growth and hematocrit values were adversely affected Histopathological anomalies of stomach, head, and trunk kidneys | Manning et al. [120]        |
| T-2 toxin | Juvenile common carp     | 1.0 or 2.0 mg·kg\(^{-1}\) | Feed: oral     | 6                           | Mortality                                                                      | Manning et al. [112]        |
| T-2 toxin | Pacific white shrimp *Litopenaeus vannamei* | 2.4 and 4.8 mg·kg\(^{-1}\) | Feed: oral     | 3                           | Decrease in growth and survival rate Antioxidant enzymes, superoxide dismutase (SOD) and glutathione peroxidase (GPx), total antioxidant capacity (T-AOC), and also glutathione (GSH) content increased SOD and GPx, T-AOC, and GSH content decreased, cell autophagy | Deng et al. [103]           |
| T-2 toxin | Pacific white shrimp *Litopenaeus vannamei* | 12.2 mg·kg\(^{-1}\) | Feed: oral     | 3                           |                                                                                  | Deng et al. [103]           |
there are also reports of DON not interfering in the weight gain of fish [132, 133].

ZEN has been implicated in reproductive disorders of farm animals [134]; however, very few studies have been done on the effect of ZEN in farmed aquatic species. In zebrafish (Danio rerio), ZEN reduced spawning frequency [126] or changed their relative fecundity from one generation to another [127]. In another study, defects in the heart

| Mycotoxin | Species | Exposure dose | Administration | Duration of exposure (weeks) | Toxicity effect | References |
|-----------|---------|---------------|----------------|------------------------------|----------------|------------|
| MON       | Channel catfish | 20, 40, 60, and 120 mg·kg⁻¹ | Feed: oral | 10 | Reductions in growth, low hematocrit level and high serum pyruvate level in the liver | Yildirim et al. [121] |
|           | Channel catfish | 60 mg·kg⁻¹ | Feed: oral | 10 | Reductions in growth and high serum pyruvate levels | Yildirim et al. [121] |
|           | Nile tilapia | 60 and 150 mg·kg⁻¹ | Feed: oral | 8 | Hematocrit was significantly low | Tuan et al. [122] |
|           | Nile tilapia | 150 mg·kg⁻¹ | Feed: oral | 8 | | Tuan et al. [122] |
|           | Channel catfish | 80, 320, or 720 mg·kg⁻¹ | Feed: oral | 14 | Reductions in growth, lower hematocrit and red cell counts, and higher white cell counts | Lumlerdtacha et al. [105] |
|           | Channel catfish | 20, 80, 320, or 720 mg·kg⁻¹ | Feed: oral | 14 | Swollen hepatocytes in the liver with lipid-containing vacuoles, lymphocyte infiltration, and scattered necrotic hepatocytes | Lumlerdtacha et al. [105] |
|           | Rainbow trout | 23 mg·kg⁻¹ | Feed: oral | 42 | Cancer promoter | Carlson et al. [123] |
|           | Nile tilapia | 40, 70, 150 mg·kg⁻¹ | Feed: oral | 8 | Lower mean weight gains | Tuan et al. [122] |
| FB₁       | Nile tilapia | 150 mg·kg⁻¹ | Feed: oral | 8 | Haematocrit was decreased and ratio between free sphinganine and free sphingosine (SA/SO) in the liver increased | Tuan et al. [122] |
|           | Common carp Cyprinus carpio | 100 and 10 mg·kg⁻¹ | Feed: oral | 6 | Blood vessels, liver, exocrine and endocrine pancreas, excretory and haematopoietic kidney, and heart and brain were sensitive | Petrinec et al. [124] |
|           | Common carp | 0.5 and 5.0 mg·kg⁻¹ | Feed: oral | 6 | Loss of body weight and alterations of haematological and biochemical parameters in target organs | Pepeljnjak et al. [125] |
|           | Common carp | 5.0 mg·kg⁻¹ | Feed: oral | 6 | Increase in bacterial infection | Pepeljnjak et al. [125] |
|           | Zebrafish Danio rerio | 1000 and 3200 ng·L⁻¹ | Feed: oral | 6 | Reduced spawning frequency | Schwartz et al. [126] |
|           | Zebrafish | 1000 ng·L⁻¹ | | 26 | Affect growth and changed relative fecundity from one generation to another | Schwartz et al. [127] |
| ZEN       | Black tiger shrimp Penaeus monodon Fabricius | 500 and 1000 mg·kg⁻¹ | Feed: oral | 10 | Histological changes in hepatopancreatic tissue | Bundit et al. [128] |
|           | Common carp | 0.332, 0.621 and 0.797 mg·kg⁻¹ | Feed: oral | 4 | No effect on growth but effects on haematological parameters | Pietsch et al. [129] |
|           | Juvenile rainbow trout | 1.810 mg·kg⁻¹ | Feed: oral | 10 | No effects on growth and may accelerate sexual maturation of female fish | Woźny et al. [130] |
and eye development and upward curvature of the body axis of were observed when zebrafish larvae were exposed to 500 µg·L⁻¹ or higher of ZEN [135]. By considering the few studies made in aquaculture species (Table 4), we would presume that ingestion of ZEN may affect growth performance, but it depends on species, dose, and duration of exposure, and it can result in complications in broodstocks of farmed species and monosex-cultured species.

Scarce information is available on the toxicity of OTA in aquatic species. A significant reduction in weight gain, poorer feed conversion rate, lower survival, and hematocrit was observed in channel catfish fed with OTA-contaminated diets [111]. Furthermore, moderate-to-severe histopathological lesions of the liver and posterior kidney were observed [113]. While a significant decrease in erythrocyte count (RBCs), haemoglobin content (Hb), and haematocrit value (Hct) in Nile tilapia exposed to low OTA level (400 µg·kg⁻¹) was seen, in Nile tilapia exposed to 600 µg·kg⁻¹ diet mean corpuscular volume (MCV), mean corpuscular haemoglobin (MCH), and mean corpuscular haemoglobin concentrate (MCHC) blood indices significantly reduced [136]. In addition, as shown in Table 4, OTA has a negative impact on shrimp even after feeding them with 1000 µg·kg⁻¹ contaminated diet for 8 weeks. However, increasing the dose and exposure duration might affect the shrimp negatively.

Other mycotoxins like sterigmatocystin, which is closely related to the aflatoxin as a precursor to aflatoxin biosynthesis and carcinogenic, have been studied in Nile tilapia [115]. Stg has genotoxic and toxicopathological effects in Nile tilapia, [115]. Stg also decreases body weight and increase in frequencies of micronucleated red blood cells (MN RBC) and chromosomal aberrations in the kidney of Nile tilapia [114]. Studies on the effects of ROQ-C on animals and fish are limited; however, CPA has been reported to cause anorexia, diarrhoea, pyrexia, dehydration, weight loss, ataxia, immobility, and extensor spasm at the time of death in several animals [33].

As shown in Tables 3 and 4, different studies highlight that mycotoxins are a serious problem to farmed aquatic species. A majority of these experiments were conducted based on chronic character, contaminated feed as the route of exposure, and several different doses. It is important to maintain standards when performing the experiments in relation to sex, as studies show that male animals are more susceptible to mycotoxin [137], divide the toxicology tests on acute, subchronic, and chronic, and also consider species, age, rearing conditions, route of exposure, and dose according to each type of mycotoxins, mainly to detect toxic effects on fish.

6. Synergistic Effect of Mycotoxins in Fish

Mycotoxins often occur concurrently [40]. Thes multiple mycotoxin contaminations in fish feeds are crucial as mycotoxins may toxicologically interact with each other eliciting marked synergistic and additive actions [138] especially between mycotoxins found at high concentrations. This might increase the negative impact of mycotoxins in farmed aquatic species at lower levels when present in single contamination. There are limited data on toxic effects of mycotoxin mixtures in farmed aquatic species [123], FB₁ was not carcinogenic when rainbow trout was fed at 0, 3, 2, 23, or 104 mg·kg⁻¹ FB₁ for a total of 34 weeks. But trout-fed FB₁ (≥23 mg·kg⁻¹ FB₁ for 42 weeks) promoted AFβ-initiated liver tumors; this result also suggests the importance of long-term contamination as a factor influencing the susceptibility of animals. He et al. [139] examined the individual and synergistic effect of DON and AFβ₁ on primary hepatocytes of common carp and inferred that the toxic effects of the combined mycotoxins were greater than the effects of single mycotoxins. McKean et al. [140] examined the synergistic effects of AFβ₁ and T-2 toxin in mosquitofish (Gambusia affinis), showing a significant additive interaction in the toxic response to the combination of mycotoxins. The cooccurrence of AF and OTA presents a health risk in fish because of their synergistic and/or additive effects [141]. Critical is that these mycotoxins can potentially be carried over to human food of animal origin and may cause public health threats [141]. To the best of our knowledge, very few studies were carried out for investigating the interacting effects of multymycotoxins in farmed aquatic animals; however, considering the previous studies carried out for other animals [142–144], we could consider that mycotoxin interactions may likewise affect negatively farmed aquatic species.

7. Conclusion

This review shows that fish feeds and their ingredients are frequently contaminated with mycotoxigenic fungi and mycotoxins. Ingredients, especially grains and oilseeds, are the main reservoirs for mycotoxins in fish feed. Ingestion of mycotoxin-contaminated feeds can affect fish health and also contributes to the economic loss of the fish farmers. Also, attention should be taken on the possible carryover of mycotoxins from feed ingredients and finished feed to the meat of farmed aquatic animals for human consumption. Hence, it is important to ensure the control of mycotoxin contamination in fish feeds and their ingredients. Use of seed coat with the small, compact grains (wheat, rice, oat, and sorghum) and those encapsulated in hard seed coats (beans and soybeans) might reduce the contamination of mycotoxin in feeds since they are less susceptible to fungal infection and mycotoxin formation than larger grains such as maize. Since mycotoxins are also produced during storage conditions, it will be important to monitor routinely raw materials as well as finished feeds. Awareness and sensitization on proper storage facilities, duration, and condition for feeds and ingredients are recommended to farmers. Antifungal agents should be used to reduce mycotoxin contamination in feed ingredients and finished fish feeds. Further research is needed to test the synergistic effects of mycotoxins when diets are contaminated with more than one mycotoxin.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
References

[1] High Level Panel of Experts (HLPE), Sustainable Fisheries and Aquaculture for Food Security and Nutrition, Food and Agriculture Organization, Rome, Italy, 2014.

[2] S. Tveeterås, F. Asche, M. F. Bellemare et al., “Fish is food—the FAO’s fish price index,” PLoS One, vol. 7, no. 5, Article ID e36731, 2012.

[3] Food and Agricultural Organisation (FAO), The State of World Fisheries and Aquaculture, Food and Agricultural Organisation (FAO), Rome, Italy, 2016.

[4] H. Charo-Karisa and M. Gichuri, “Overview of the fish farming enterprise productivity program,” in End of Year Report Fish Farming Enterprise Productivity Program Phase I, Aquaculture Development Working Group, Nairobi, Kenya, 2010.

[5] A. Anater, L. Manyes, G. Meca et al., “Mycotoxins and their consequences in aquaculture: a review,” Aquaculture, vol. 451, pp. 1–10, 2016.

[6] C. C. Alceste and D. E. Jory, “Tilapia-alternative protein sources in tilapia feed formulation,” Aquaculture Magazine, vol. 26, pp. 70–75, 2000.

[7] E. Kjœrsvik, A. Mangor-Jensen, and I. Holmejford, “Egg quality in fishes,” Advances in Marine Biology, vol. 26, pp. 71–113, 1990.

[8] D. M. Liti, R. M. Mugo, J. M. Munguti, and H. Waidbacher, “Growth and economic performance of Nile tilapia (Oreochromis niloticus L.) fed on three brans (maize, wheat and rice) in fertilized ponds,” Aquaculture Nutrition, vol. 12, no. 3, pp. 239–245, 2006.

[9] D. Liti, L. Cherop, J. Munguti, and L. Chhorn, “Growth and economic performance of Nile tilapia (Oreochromis niloticus L.) fed on two formulated diets and two locally available feeds in fertilized ponds,” Aquaculture Research, vol. 36, no. 8, pp. 746–752, 2005.

[10] J. F. Almeida, H. M. L. Martins, S. M. O. Santos, M. S. Freitas, J. M. G. N. da Costa, and F. M D’Almeida Bernardo, “Mycobiota and aflatoxin B1 in feed for farmed sea bass (Dicentrarchus labrax),” Toxins, vol. 3, no. 3, pp. 163–171, 2011.

[11] J. W. Bennett and M. Klich, “Mycotoxins,” Clinical Microbiology Reviews, vol. 16, no. 3, pp. 497–516, 2003.

[12] M. E. Zain, “Impact of mycotoxins on humans and animals,” Journal of Saudi Chemical Society, vol. 15, no. 2, pp. 129–144, 2011.

[13] S. Bankole, M. Schollenberger, and W. Drochner, “Mycotoxins in food systems in sub saharan Africa: a review,” Mycotoxin Research, vol. 22, no. 3, pp. 163–169, 2006.

[14] M. C. Chávez-Sánchez, C. A. Martínez Palacios, and I. Osorio Moreno, “Pathological effects of feeding young Oreochromis niloticus diets supplemented with different levels of aflatoxin B1,” Aquaculture, vol. 127, no. 1, pp. 49–60, 1994.

[15] F. Berthiller, M. Sulyok, R. Krksa, and R. Schuhmacher, “Chromatographic methods for the simultaneous determination of mycotoxins and their conjugates in cereals,” International Journal of Food Microbiology, vol. 119, no. 1-2, pp. 33–37, 2007.

[16] J. I. Pitt, “Toxigenic fungi and mycotoxins,” British Medical Bulletin, vol. 56, no. 1, pp. 184–192, 2000.

[17] W. L. Bryden, “Mycotoxin contamination of the feed supply chain: implications for animal productivity and feed security,” Animal Feed Science and Technology, vol. 173, no. 1-2, pp. 134–158, 2012.

[18] Y. Huang, D. Han, X. Xiao et al., “Effect of dietary aflatoxin B1 on growth, fecundity and tissue accumulation in gibel carp during the stage of gonad development,” Aquaculture, vol. 428–429, pp. 236–242, 2014.

[19] A. Caganaan and R. Tayaban, “Effect of aflatoxin-contaminated feeds in Nile tilapia (Oreochromis niloticus L.),” in Proceedings of the 6th International Symposium on Tilapia Aquaculture, pp. 172–178, Manila, Philippines, September 2004.

[20] M. E. Mahfouz and A. H. Sherif, “A multiparameter investigation into adverse effects of aflatoxin on Oreochromis niloticus health status,” The Journal of Basic & Applied Zoology, vol. 71, pp. 48–59, 2015.

[21] E. Marijami, J. Nasimilo, E. Kigadye, G. J. B. Gnonlonfin, and S. Okoth, “Sex-related differences in hematological parameters and organosomatic indices of Oreochromis niloticus exposed to aflatoxin B1 diet,” Scientifica, vol. 2017, Article ID 4268926, p. 7, 2017.

[22] W. Jantrarotai and R. T. Lovell, “Subchronic toxicity of dietary aflatoxin B1 to channel catfish,” Journal of Aquatic Animal Health, vol. 2, no. 4, pp. 248–254, 1990.

[23] M. P. Santacroce, M. C. Conversano, E. Casalino et al., “Aflatoxins in aquatic species: metabolism, toxicity and perspectives,” Reviews in Fish Biology and Fisheries, vol. 18, no. 1, pp. 99–130, 2008.

[24] S. Craig and L. A. Helfrich, Understanding Fish Nutrition, Feeds, and Feeding, Virginia Cooperative Extension, Blacksburg, VA, USA, 2002.

[25] A. G. J. Tacon, Nutritional Fish Pathology: Morphological Signs of Nutrient Deficiency and Toxicity in Farmed Fish, Food and Agriculture Organization of the United Nations, Rome, Italy, 4th edition, 1992.

[26] H. Zhao, R. Jiang, M. Xue, S. Xie, X. Wu, and L. Guo, “Fishmeal can be completely replaced by soy protein concentrate by increasing feeding frequency in Nile tilapia (Oreochromis niloticus GIFT strain) less than 2 g,” Aquaculture Nutrition, vol. 16, no. 6, pp. 648–653, 2010.

[27] C. C. Ngugi and J. O. Manyala, Aquaculture Extension in Sub-Saharan Africa, Food and Agriculture Organization, Rome, Italy, 2004.

[28] P. Spring, D. F. Fegan, T. P. Lyons et al., “Mycotoxins—a rising threat to aquaculture,” in Proceedings of the Alltech’s 23rd Annual Symposium, pp. 323–331, Alltech UK, Lexington, KY, USA, 2005.

[29] R. a. Samson, J. Houbenken, U. Thrane et al., “Food and Indoor Fungi,” in CBS Lab. Man., Ser., A. Robert and C.-K. F. B. C. Samson, Eds., CBS-KNAW Fungal Biodiversity Centre, 2010.

[30] J. C. Frisvad, T. O. Larsen, U. f+hørane et al., “Fumonisin and ochratoxin production in industrial Aspergillus niger strains,” PLoS One, vol. 6, no. 8, Article ID e23496, 2011.

[31] K. J. Kwon-Chung and J. A. Sugui, “What do we know about the role of gliotoxin in the pathobiology of Aspergillus fumigatus?,” Medical Mycology, vol. 47, pp. 97–103, 2009.

[32] B. L. Rao and A. Hussain, “Presence of cyclopiazonic acid in kodo millet (Paspalum scrobiculatum) causing koda poisoning in man and its production by associated fungi,” Mycopathologia, vol. 89, no. 3, pp. 177–180, 1985.

[33] B. Caballero, P. Finglas, and F. Toldra, Encyclopeda of Food Sciences and Nutrition, Academic Press, Cambridge, MA, USA, 2nd edition, 2003.

[34] H. M. A. Mohamed, W. F. A. Emeish, A. Braeunling, and S Hammad, “Detection of aflatoxin-producing fungi isolated from...”
from Nile tilapia and fish feed,” EXCLI Journal, vol. 16, pp. 1308–1318, 2017.

35. E. Marjani, J. M. Wainaina, H. Charo-Karisa et al., “Mycoflora and mycotoxins in finished fish feed and feed ingredients from smallholder farms in East Africa,” The Egyptian Journal of Aquatic Research, vol. 43, no. 2, pp. 169–176, 2017.

36. G. Njagi, “Isolation of fungal agents from formulated and commercial feeds in three fish farms in humid tropical environments of Kenya,” in Proceedings of the 5th Annual National Biosafety Conference, National Biosafety Authority, Nairobi, Kenya, August 2016.

37. E. M. C. Gonçalves-Nunes, M. M. Gomes-Pereira, G. Njagi, “Isolation of fungal agents from formulated and commercial feeds in three fish farms in humid tropical environments of Kenya,” in Proceedings of the 5th Annual National Biosafety Conference, National Biosafety Authority, Nairobi, Kenya, August 2016.

38. M. Greco, A. G. Pardo, and G. Pose, “Mycotoxicogenic fungi and natural occurrence of mycotoxins in rainbow trout (Oncorhynchus mykiss) feeds,” Toxins, vol. 7, no. 11, pp. 4595–4609, 2015.

39. A. A. Fallah, E. Pirali-Kheirabadi, M. Rahnama, S. S. Saeidi, M. Greco, A. Pardo, and G. Pose, “Mycotoxigenic fungi and mycobiota related to raw materials and finished feed destined for fish,” Latin American Journal of Aquatic Research, vol. 43, pp. 595–600, 2015.

40. M. Greco, A. Pardo, and G. Pose, “Mycotoxicogenic fungi and natural occurrence of mycotoxins in rainbow trout (Oncorhynchus mykiss) feeds,” Toxins, vol. 7, no. 11, pp. 4595–4609, 2015.

41. F. D. C. C. Filho, R. M. Calvet, C. A. Da Rocha Rosa et al., “Screening of aflatoxin B1 and mycobiota related to raw materials and finished feed destined for fish,” African Journal of Microbiology Research, vol. 6, no. 4, pp. 419–424, 2014.

42. T. S. Barbosa, C. M. Pereyra, C. A. Soleiro et al., “Mycobiota and mycotoxins present in finished feed from farms in the Rio de Janeiro State, Brazil,” International Aquatic Research, vol. 5, no. 1, p. 3, 2013.

43. F. D. C. C. Filho, R. M. Calvet, C. A. Da Rocha Rosa et al., “Screening of aflatoxin B1 and mycobiota related to raw materials and finished feed destined for fish,” African Journal of Microbiology Research, vol. 6, no. 4, pp. 419–424, 2014.

44. T. S. Barbosa, C. M. Pereyra, C. A. Soleiro et al., “Mycobiota and mycotoxins present in finished feed from farms in the Rio de Janeiro State, Brazil,” International Aquatic Research, vol. 5, no. 1, pp. 3–9, 2013.

45. C. H. Rodriguez-Cervantes, A. J. Ramos, M. L. Robledo-Marenco, V. Sanchis, S. Marin, and M. I. Girón-Pérez, “Determination of aflatoxin and fumonisin levels through ELISA and HPLC, on tilapia feed in Nayarit, Mexico,” Food and Agricultural Immunology, vol. 24, no. 3, pp. 269–278, 2013.

46. S. Alinezhad, M. Tolouee, A. Kamalzadeh et al., “Mycobiota and aflatoxin B1 contamination of rainbow trout (Oncorhynchus mykiss) feeds with emphasis to Aspergillus section Flavi and aflatoxins in fish feed,” Quality Assurance and Safety of Crops & Foods, vol. 6, no. 4, pp. 419–424, 2014.

47. A. Hassan, M. El Shafei, M. S. El Ahl et al., “Detection of aflatoxigenic moulds isolated from fish and their products and its public health significance,” Nature and Science, vol. 9, pp. 106–114, 2011.

48. S. K. Mutiga, V. Hoffmann, J. W. Harvey, M. G. Milgroom, and R. J. Nelson, “Assessment of aflatoxin and fumonisin contamination of maize in Western Kenya,” Phytopathology, vol. 105, no. 9, pp. 1250–1261, 2015.

49. S. Yazar and G. Omurtag, “Fumonisins, trichotheccenes and zearalenone in cereals,” International Journal of Molecular Sciences, vol. 9, no. 11, pp. 2062–2090, 2008.

50. D. Ivić, A.-M. Domijan, M. Peraica, T. Milčević, and B. Cvjetković, “Fusarium spp. contamination of wheat, maize, soybean, and pea in Croatia,” Archives of Industrial Hygiene and Toxicology, vol. 60, no. 4, pp. 435–442, 2009.

51. International Agency for Research on Cancer (IARC), Fungi Producing Significant Mycotoxins, International Agency for Research on Cancer, Lyon, France, 2012.

52. J. Doughari, “The occurrence, properties and significance of citrinin mycotoxin,” Journal of Plant Pathology & Microbiology, vol. 6, no. 11, 2015.

53. C. Scharl, “Introduction to the toxins special issue on ergot alkaloids,” Toxins, vol. 7, no. 10, pp. 4232–4237, 2015.

54. P. Skouboe, J. C. Frisvad, J. W. Taylor, D. Laurissen, M. Boysen, and L. Rossen, “Phylogenetic analysis of nucleotide sequences from the ITS region of verticillate Penicillium species,” Mycological Research, vol. 103, no. 7, pp. 873–881, 1999.

55. I. El-Kady, S. El-Maraghy, and A. N. Zohri, “Mycotoxin production potential of some isolates of Aspergillus flavus and Eurotium species from meat products,” Microbiological Research, vol. 149, no. 3, pp. 297–307, 1994.

56. M. V. Greco, A. G. Pardo, G. N. Pose, and A. R. Patriarca, “Efecto de la actividad del agua y la temperatura en el crecimiento de especies de Eurotium aisladas de alimentos para animales,” Revista Iberoamericana de Micología, vol. 35, no. 1, pp. 39–48, 2018.

57. A. Pittet, “Natural occurrence of mycotoxins in foods and feeds—an updated review,” Revue De Medecine Veterinaire, vol. 149, pp. 479–492, 1998.

58. K. R. N. Reddy, S. B. Nurdijati, and B. Salleh, “An overview of plant-derived products on control of mycotoxicogenic fungi and mycotoxins,” Asian Journal of Plant Sciences, vol. 9, no. 3, pp. 126–133, 2010.

59. A. N. Kaaya and D. Eboku, “Mould and aflatoxin contamination of dried cassava chips in eastern Uganda: association with traditional processing and storage practices,” Journal of Agricultural Sciences, vol. 10, no. 8, pp. 718–729, 2010.

60. M. N. Sallam, Insect Damage: Damage on Post-Harvest, Food and Agriculture Organization, Rome, Italy, 1999.

61. C. Thompson and S. E. Henke, “Effect of climate and type of storage container on aflatoxin production in corn and its associated risks to wildlife species,” Journal of Wildlife Diseases, vol. 36, no. 1, pp. 172–179, 2000.

62. D. L. Proctor, Grain Storage Techniques: Evolution and Trends in Developing Countries, Food and Agriculture Organization, Rome, Italy, 1994.

63. H. K. Abbas, M. A. Weaver, R. M. Zabloutowicz, B. W. Horn, and W. T. Shier, “Relationships between aflatoxin production and sclerotia formation among isolates of Aspergillus section Flavi from the Mississippi Delta,” European Journal of Plant Pathology, vol. 112, no. 3, pp. 283–287, 2005.

64. H. K. Abbas, R. D. Cartwright, W. T. Shier et al., “Natural occurrence of fumonisins in rice with Fusarium sheath rot disease,” Plant Disease, vol. 82, no. 1, pp. 22–25, 1998.

65. K. A. Scudamore, S. Nawaz, M. T. Hetmanski, and S. C. Rainbird, “Mycotoxins in ingredients of animal feeding stuffs: III. determination of mycotoxins in rice bran,” Food Additives and Contaminants, vol. 15, no. 2, pp. 185–194, 1998.

66. M. R. Laubscher, “Mycotoxin contamination of abalone feed: health and safety considerations for the abalone aquaculture industry,” Ph. D. thesis, Stellenbosch University, Stellenbosch, South Africa, 2016.

67. C. Pietsch, S. Kersten, P. Burkhardt-Holm, H. Valenta, and C. Pietsch, S. Kersten, P. Burkhardt-Holm, H. Valenta, and C. Pietsch, “Occurrence of deoxynivalenol and zearalenone in commercial fish feed: an initial study,” Toxins, vol. 5, no. 1, pp. 184–192, 2013.

68. E. W. Mwihia, P. G. Mumbi, G. S. Erikson et al., “Occurrence and levels of aflatoxins in fish feeds and their potential effects on fish in Nyeri, Kenya,” Toxins, vol. 10, no. 12, pp. 543, 2018.
[66] Food and Drugs Authority, Chemical Contaminants, Metals, Natural Toxins & Pesticides—Guidance for Industry and FDA: Advisory Levels for Deoxynivalenol (DON) in Finished Wheat Products for Human Consumption and Grains and Grain By-Products Used for Animal Feed, Center for Food Safety and Applied Nutrition, College Park, MD, USA, 2010.

[67] European Commission, “Recommendation of 17 August 2006 on the presence of deoxynivalenol, zearalenone, ochratoxin A, T-2 and HT-2 and fumonisins in products intended for animal feeding,” Official Journal of the European Union, vol. L229/7–L229/9, 2006.

[68] S. A. Odoemelam and C. I. Osu, “Evaluation of the phytochemical content of some edible grains marketed in Nigeria,” E-Journal of Chemistry, vol. 6, no. 4, pp. 1193–1199, 2009.

[69] M. Kholife, A. Moawad, A. M. Diab, and A. El-keredy, “Mycological examination of fish feed stuff with special reference to mycotoxicosis production,” Slovenian Veterinary Research, vol. 56, no. 22, 2019.

[70] G. Altug and G. Beklevik, “Level of aflatoxin in some fish feeds from fish farming processes, feed factories and imported feeds,” Turkish Journal of Veterinary and Animal Sciences, vol. 27, no. 6, pp. 1247–1252, 2003.

[71] E. H. Hashimoto, M. Kamogae, T. P. Vanzella et al., “Bio-monitoring of microcystin and aflatoxin co-occurrence in aquaculture using immunohistochemistry and genotoxicity assays,” Brazilian Archives of Biology and Technology, vol. 55, no. 1, pp. 151–159, 2012.

[72] M. Hussaini, D. Michael, N. Patrick, G. Timothy, and O. Godwin, “Aflatoxin contamination in foods and feeds: a special focus on Africa,” in Trends in Vital Food and Control Engineering, pp. 187–234, Books on Demand, Norderstedt, Germany, 2012.

[73] I. Rodrigues, J. Handl, and E. M. Binder, “Mycotoxin occurrence in commodities, feed and feed ingredients sourced in the Middle East and Africa,” Food Additives and Contaminants: Part B, vol. 4, no. 3, pp. 168–179, 2011.

[74] J. A. Mmongoyo, F. Wu, J. E. Linz et al., “Aflatoxin levels in sunflower seeds and cakes collected from micro- and small-scale sunflower oil processors in Tanzania,” PLoS One, vol. 12, no. 4, Article ID e0175801, 2017.

[75] J. H. Daniel, L. W. Lewis, Y. A. Redwood et al., “Comprehensive assessment of maize aflatoxin levels in eastern Kenya, 2005–2007,” Environmental Health Perspectives, vol. 119, no. 12, pp. 1794–1799, 2011.

[76] K. R. N. Reddy and B. Salleh, “Co-occurrence of moulds and mycotoxins in corn grains used for Animal Feeds in Malaysia,” Journal of Animal and Veterinary Advances, vol. 10, no. 5, pp. 668–673, 2011.

[77] P. Jayaraman and I. Kalyanasundaram, “Natural occurrence of toxigenic fungi and mycotoxins in rice bran,” Mycopathologia, vol. 110, no. 2, pp. 81–85, 1990.

[78] F. Zaboli, A. R. Khoosavi, I. Gholampourazizi et al., “A study of aflatoxins production in rice bran from Mazandaran Province, Northern Iran,” Global Veterinaria, vol. 5, no. 1, pp. 39–44, 2010.

[79] L. Pinotti, M. Ottoboni, C. Giromini, V. Dell’Orto, and F. Cheli, “Mycotoxic contamination in the EU feed supply chain: a focus on cereal byproducts,” Toxins, vol. 8, no. 2, p. 45, 2016.

[80] O. A. Danell, O. Danell Ochi, A. Adejumo et al., “Mycotoxicological concerns with sorghum, millet and sesame in Northern Nigeria,” Journal of Analytical & Bioanalytical Techniques, vol. 7, no. 5, 2016.

[81] E. Marijani, Occurrence of Mycotoxins in Fish Feeds and Fish with Special Regard to Aflatoxin Effect on Eggs and Milt Quality of Oreochromis niloticus, Open university of Tanzania, Dar es Salaam, Tanzania, 2018.

[82] J. B. Da Silva, C. R. Pozzi, M. A. B. Mallozzi, E. M. Ortega, and B. Corrêa, “Mycollora and occurrence of aflatoxin B1 and fumonisin B1 during storage of Brazilian sorghum,” Journal of Agricultural and Food Chemistry, vol. 48, no. 9, pp. 4352–4356, 2000.

[83] P. H. Shetty and R. V. Bhat, “Natural occurrence of fumonisin B1and its Co-occurrence with aflatoxin B1 in Indian sorghum, maize, and poultry feeds,” Journal of Agricultural and Food Chemistry, vol. 45, no. 6, pp. 2170–2173, 1997.

[84] R. Bandyopadhyay, M. Kumar, and J. F. Leslie, “Relative severity of aflatoxin contamination of cereal crops in West Africa,” Food Additives and Contaminants, vol. 24, no. 10, pp. 1109–1114, 2007.

[85] E. Streit, G. Schatzmayr, P. Tassili et al., “Current situation of mycotoxic contamination and co-occurrence in animal feed—focus on Europe,” Toxins, vol. 4, no. 10, pp. 788–809, 2012.

[86] G. A. Santos, I. A. d. S. Rodrigues, K. Nachrer, and P. Encarnação, “Mycotoxins in aquaculture: occurrence in feed components and impact on animal performance,” in Avances en Nutrición Acuícola X-Memorias del Décimo Simposio Internacional de Nutrición, pp. 502–513, Universidad Autónoma de Nuevo León, San Nicolás de los Garza, Mexico, 2010.

[87] C. Nyangi, “Aflatoxins and fumonisin contamination of marketed maize, maize bran and maize used as animal feed in Northern Tanzania,” African Journal of Food, Agriculture, Nutrition and Development, vol. 16, no. 3, pp. 11054–11065, 2016.

[88] R. Gamanya and L. Sibanda, “Survey of Fusarium moniliforme (F. verticillioides) and production of fumonisin B1 in cereal grains and oilseeds in Zimbabwe,” International Journal of Food Microbiology, vol. 71, no. 2–3, pp. 145–149, 2001.

[89] S. G. Edwards, E. T. Dickin, S. MacDonald et al., “Distribution of Fusarium mycotoxins in UK wheat mill fractions,” Food Additives & Contaminants: Part A, vol. 28, no. 12, pp. 1694–1704, 2011.

[90] M. F. Olorunfemi, A. C. Odeboke, O. O. Olawuyi, and C. N. Ezekiel, “Multi-mycotoxin contaminations in fish feeds from different agro-ecological zones in Nigeria,” in Proceedings of the Tropentag 2013 International Research on Food Security, Natural Resource Management and Rural Development, Stuttgart, Germany, September 2013.

[91] R. A. Goncalves, K. Nachrer, and G. A. Santos, “Occurrence of mycotoxins in commercial aquafeeds in Asia and Europe: a real risk to aquaculture?,” Reviews in Aquaculture, vol. 10, no. 2, pp. 263–280, 2018.

[92] H. H. L. Gonzalez, E. J. Martinez, A. M. Pacin, S. L. Resnik, and E. W. Sydenham, “Natural co-occurrence of fumonisins, deoxynivalenol, zearalenone and aflatoxins in field trial corn in Argentina,” Food Additives and Contaminants, vol. 16, no. 12, pp. 565–569, 1999.

[93] C. M. Placinta, J. P. F. D’Mello, and A. M. C. MacDonald, “A review of worldwide contamination of cereal grains and animal feed with Fusarium mycotoxins,” Animal Feed Science and Technology, vol. 78, no. 1-2, pp. 21–37, 1999.

[94] I. Pleadin, J. Frece, T. Lesi et al., “Deoxynivalenol and zearalenone in unprocessed cereals and soybean from...
different cultivation regions in Croatia," Food Additives & Contaminants: Part B, vol. 10, pp. 1–7, 2017.

[95] S. Tola, D. Bureau, J. Hooft et al., "Effects of wheat naturally contaminated with Fusarium mycotoxins on growth performance and selected health indices of red Tilapia (Oreochromis niloticus × O. mossambicus)," Toxins, vol. 7, no. 6, pp. 1929–1944, 2015.

[96] M. Woźny, K. Obremski, E. Jakimiuk, M. Guziatin, and P. Brzuzan, "Zearalenone contamination in rainbow trout farms in north-eastern Poland," Aquaculture, vol. 416–417, pp. 209–211, 2013.

[97] C. Lanier, N. Heutte, E. Richard, V. Bouchart, P. Lebailly, and D. Garon, "Mycoflora and mycotoxicosis production in oilseed cakes during farm storage," Journal of Agricultural and Food Chemistry, vol. 57, no. 4, pp. 1640–1645, 2009.

[98] Y. S. El-Sayed and R. H. Khalil, "Toxicity, biochemical effects and residue of aflatoxin B1 in marine water-reared sea bass (Dicentrarchus labrax L.)," Food and Chemical Toxicology, vol. 47, no. 7, pp. 1606–1609, 2009.

[99] H. Nomura, M. Ogiso, M. Yamashita et al., "Uptake by Oncorhynchus mykiss of aflatoxin B1 during long-term dietary exposure and elimination of aflatoxins in muscle and liver of rainbow trout (Oncorhynchus mykiss)," Journal of Agricultural and Food Chemistry, vol. 59, no. 9, pp. 5150–5158, 2011.

[100] J. M. Hooft, A. E. H. I. Elmor, P. Encarnação, and D. P. Bureau, "Rainbow trout (Oncorhynchus mykiss) is extremely sensitive to the feed-borne Fusarium mycotoxicosis deoxynivalenol (DON)," Aquaculture, vol. 311, no. 1–4, pp. 224–232, 2011.

[101] R. El-Banna, H. M. Teleb, M. M. Hadi, and F. M. Fakhry, "Performance and tissue residue of tilapias fed dietary aflatoxin," Veterinary Medical Journal, vol. 40, no. 3, pp. 17–23, 1992.

[102] N. A. Tuan, J. M. Grizzle, R. T. Lovell, B. B. Manning, and G. E. Rottinghaus, "Growth and hepatic lesions of Nile tilapia (Oreochromis niloticus) fed diets containing aflatoxin B1," Aquaculture, vol. 212, no. 1–4, pp. 311–319, 2002.

[110] P. K. Sahoo and S. C. Mukherjee, "Immunosuppressive effects of aflatoxin B1 in Indian major carp (Labeo rohita)," Comparative Immunology, Microbiology and Infectious Diseases, vol. 24, no. 3, pp. 143–149, 2001.

[111] B. B. Manning, R. M. Ulhoa, M. H. Li, E. H. Robinson, and G. E. Rottinghaus, "Ochratoxin A fed to channel catfish (Ictalurus punctatus) causes reduced growth and lesions of hepatopancreatic tissue," Aquaculture, vol. 219, no. 1–4, pp. 739–750, 2003.

[112] B. B. Manning, J. S. Terhune, M. H. Li, E. H. Robinson, D. J. Wise, and G. E. Rottinghaus, "Exposure to feedborne mycotoxins T-2 toxin or ochratoxin a causes increased mortality of channel catfish challenged with Edwardsiella ictaluri," Journal of Aquatic Animal Health, vol. 17, no. 2, pp. 147–152, 2005.

[121] M. Yildirim, B. B. Manning, R. T. Lovell, J. M. Grizzle, and G. E. Rottinghaus, "Toxicity of moniliformin and fumonisin B1 fed singly and in combination in diets for young channel catfish Ictalurus punctatus," Journal of the World Aquaculture Society, vol. 31, no. 4, pp. 599–608, 2007.
fumonisin B1," *Aquaculture*, vol. 217, no. 1–4, pp. 515–528, 2003.

[123] D. B. Carlson, D. E. Williams, J. M. Spitsbergen et al., “Fumonisin B1 promotes aflatoxin B1 and N-methyl-N-nitro-nitrosoguanidine-Initiated liver tumors in rainbow trout,” *Toxicology and Applied Pharmacology*, vol. 172, no. 1, pp. 29–36, 2001.

[124] Z. Petrinec, S. Pepeljnjak, S. Kovacic et al., “Fumonisin B1 causes multiple lesions in common carp (*Cyprinus carpio*),” Deutsche Tierärztliche Wochenschrift, vol. 111, pp. 358–363, 2004.

[125] S. Pepeljnjak, Z. Petrinec, S. Kovacic, and M. Segvic, “Screening toxicity study in young carp (*Cyprinus carpio* L.) on feed amended with fumonisin B1,” *Mycopathologia*, vol. 156, no. 2, pp. 139–145, 2003.

[126] P. Schwartz, K. L. Thorpe, T. D. Bucheli, F. E. Wettstein, and P. Burkhardt-Holm, "Short-term exposure to the environmentally relevant estrogenic mycotoxin zearalenone impairs reproduction in fish," *Science of The Total Environment*, vol. 409, no. 2, pp. 326–333, 2010.

[127] P. Schwartz, T. D. Bucheli, F. E. Wettstein, and P. Burkhardt-Holm, "Life-cycle exposure to the estrogenic mycotoxin zearalenone affects zebrafish (*Danio rerio*) development and reproduction," *Environmental Toxicology*, vol. 28, no. 5, pp. 276–289, 2013.

[128] O. Bundit, W. Phromkunthong, H. Kanghae, and K. Supamattaya, "Effects of mycotoxin T-2 and zearalenone on histopathological changes in black tiger shrimp (*Penaeus monodon Fabricius*)," *Songklanakarin Journal of Science and Technology*, vol. 28, no. 5, 2006.

[129] C. Pietsch, S. Kersten, H. Valenta et al., "Effects of dietary exposure to zearalenone (ZEN) on carp (*Cyprinus carpio* L.)," *Toxins*, vol. 7, no. 9, pp. 3465–3480, 2015.

[130] M. Woźniy, S. Dobosz, K. Obremski et al., "Feed-borne exposure to zearalenone leads to advanced ovarian development and limited histopathological changes in the liver of premarket size rainbow trout," *Aquaculture*, vol. 448, pp. 71–81, 2015.

[131] F. I. Meredith, R. T. Riley, C. W. Bacon, D. E. Williams, and D. B. Carlson, "Extraction, quantification, and biological availability of fumonisin B1 incorporated into the oregon test diet and fed to rainbow trout," *Journal of Food Protection*, vol. 61, no. 8, pp. 1034–1038, 1998.

[132] C. Pietsch, C. Michel, S. Kersten et al., "In vivo effects of deoxynivalenol (DON) on innate immune responses of carp (*Cyprinus carpio* L.)," *Food and Chemical Toxicology*, vol. 68, pp. 44–52, 2014.

[133] M. Sanden, S. Jørgensen, G.-I. Hemre, R. Ørsnud, and N. H. Sissener, “Zebrafish (*Danio rerio*) as a model for investigating dietary toxic effects of deoxynivalenol contamination in aquaculture feeds,” *Food and Chemical Toxicology*, vol. 50, no. 12, pp. 4441–4448, 2012.

[134] F. Minervini and M. E. Dell’Aquila, “Zearalenone and reproductive function in farm animals,” *International Journal of Molecular Sciences*, vol. 9, no. 12, pp. 2570–2584, 2008.

[135] K. Bakos, R. Kovács, Á. Staszny et al., "Developmental toxicity and estrogenic potency of zearalenone in zebrafish (*Danio rerio*)," *Aquatic Toxicology*, vol. 136-137, pp. 13–21, 2013.

[136] A. M. E. Shalaby, “The opposing effect of ascorbic acid (vitamin C) on ochratoxin toxicity in Nile tilapia (*Oreochromis niloticus*),” in *Proceedings of the 6th International Symposium on Tilapia in Aquaculture*, pp. 209–221, Manila, Philippines, September 2004.