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Current Status of Major Mycotoxins Contamination in Food and Feed in Asia—A Review

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ABSTRACT: Mycotoxins can cause genotoxic, mutagenic, teratogenic, and carcinogenic effects in humans and animals. Mycotoxins inevitably exist widely in all kinds of food and feed commodities, of which cereals are the most susceptible. In one of the largest cereal producing and consuming regions in the world, mycotoxin contamination causes about 1 billion metric tons of food loss annually, which also influences a serious decline of Asian economic development. This Review is based on three databases, PubMed, Google Scholar, and Web of Science, including studies that were published in English in the period from January 1, 2016 to October 1, 2022. Results show the current status and control strategies of the aflatoxins, ochratoxin A, zearalenone, deoxynivalenol, and fumonisins in Asia. Developed countries in Asia should maintain strict monitoring and establish an effective control system for the whole food production chain, while developing countries should strengthen the prevention and control strategies for mycotoxins.

KEYWORDS: *Mycotoxins contamination, Agricultural product, Food and feed, Asia, Prevention and control strategies*

1. INTRODUCTION

Mycotoxins are toxic secondary metabolites mainly produced by filamentous fungi.[1] As insidious poisons, mycotoxins are difficult to detect in food and feed, and their contamination is of great concern to public health and causes economic losses to crops and the food sector. The toxicity expressed by mycotoxins can be acute, chronic, or both depending on the type and dose ingested. Adverse health effects could be caused by consuming mycotoxin contaminated food/feed, such as liver and kidney damage and genotoxic, mutagenic, teratogenic, and carcinogenic effects.[2,3] Mycotoxins are classified in various ways based on their structural and functional variations. Liver cancer is more common in some regions of southeastern Asia than in other parts of the world, and it may appear with increased exposure to aflatoxins.[4] Moreover, the economic losses caused by mycotoxin contamination could not be ignored. Mycotoxin contamination has adverse effects on the food chain, especially severely affecting corn and maize yields, which eventually disturbs economic outcomes.[5]

It is difficult to prevent and control mycotoxin contamination in the food chain. The infection of molds can occur at various stages of food and feed production. Mycotoxin-producing fungi have a chance to invade crops in different periods. During preharvest, harvest, postharvest, and even in storage conditions, toxigenic fungi may invade grains. The toxigenic fungi can be divided into field fungi, storage fungi, and advanced deterioration fungi according to the respective periods of fungi infection of grains.[6] In addition, there are numerous factors affecting the growth of molds, such as food species/feed types, water activity (a_w), temperature, the availability of nutrients and oxygen, food processing, and chemical additives.[7,8] In order to prevent the production of mycotoxins, it is essential to control these parameters during various stages of food production and storage. Given the hot and humid climate of South and Southeast Asia, it is suitable for fungal growth and mycotoxin production.[9] In addition, most of Asia is developing countries with high sociocultural differences and high variability in food system dynamics.[10] Each region has its own unique risk factors, and it is necessary to establish a suitable prevention and control modeling framework to reduce mycotoxin contamination based on its own reality.

The high incidence of mycotoxins leads to serious issues in Asia. Asia is the largest producer and consumer region of rice; about 87% of the world's total rice production is from the Asian region. In China (East Asia), more than 65% of the population consumes rice as a staple food.[11] Rice can be contaminated with aflatoxins (AFs) and ochratoxin A (OTA), as well as fumonisins, which could cause serious damage to the liver and kidneys.[12,13] Moreover, the co-occurrence of mycotoxins has been found in grains and may result in additive or synergistic toxicity.[14] In South Asia, biomonitoring data in Bangladeshi adults indicated a frequent exposure to the nephrotoxic mycotoxins such as OTA. The results showed that their exposure levels were significantly higher than those of Europeans. This may be related to the diet difference and food contamination such as rice and spices.[15] In Southeast Asia, although efforts and measures have been made to reduce AF contamination, the high incidence of aflatoxins is still paralleled

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with the high occurrence of aflatoxicosis.[16] In Iran (West Asia), 76.6% of white wheat flour was found contaminated with OTA.[17] The exposure of deoxynivalenol (DON) in Asia is worth noting due to cumulative health risks related to DON.[18] A previous study revealed that 70.2% of feed samples in Taiwan, China (East Asia) were detected to be contaminated with zearalenone (ZEN).[19]

According to FAO data in 2010, Asian cereal production accounts for about 49.62% of global cereal production, making it one of the world's largest cereal food and feed producing regions.[20] However, mycotoxin contamination causes about 1 billion metric tons of food loss annually, which influences a serious decline in economic development and public health in Asia. In order to reduce the food and feed loss caused by mycotoxin contamination in Asia, it is essential to summarize findings from previous reports and research. This review is aimed at (1) researching the current status of the major mycotoxins causing food and feed contamination in Asia and (2) providing some possible prevention and control strategies for mycotoxins contamination in Asia.

2. MATERIALS AND METHOD

This literature search was performed using databases (including PubMed, Google Scholar, Web of Science, etc.) with any information regarding the contamination of aflatoxins, ochratoxin A, zearalenone, deoxynivalenol, and fumonisins in each Asian country.

This literature search also used the U.S. Food and Drug Administration (FDA), European Commission (EC), China Food and Drug Administration (CFDA), and Korea Food and Drug Administration (KFDA) databases as the maximum allowable level reference.

Information regarding the Rapid Alert System for Food and Feed (RASFF) can be found on their Web site.

The search was limited to English and with a time frame restriction from 2016 to 2022. After reading the articles with relevant information and removing duplicate citations, a total of 125 relevant articles were cited in this literature review.

3. RESULT AND DISCUSSION

3.1. Major Mycotoxins Causing Food and Feed Contamination in Asia. The contamination caused by AFs, OTA, ZEN, DON, and fumonisins is a serious problem which should be taken into consideration as having an impact on public health and the food trade in Asia. Not only are they associated with health problems, but they are also among the few mycotoxins considered the most important from an economic point of view.[21] These five kinds of mycotoxins are widely found in the main food and feed ingredients in Asia and are subject to legal regulations in various countries of Asia.

3.1.1. The Contamination of AFs in Food and Feed. AFs are secondary metabolites primarily produced by several species of *Aspergillus* genus, mainly *Aspergillus flavus* and *Aspergillus parasiticus*.[22] The Asian continent is large in area (44 million square kilometers), spanning a wide range of latitudes and crossing frigid zones, temperate zones, and tropical zones, which results in a complex and diverse climate. The tropical climate with characteristics of high temperature and humidity in west Asia, south Asia, and southeast Asia favors the growth of fungi from *A. flavus*.[23] *Aspergillus* species produce different types of AFs, including the aflatoxins B_1, B_2, G_1, and G_2 under natural conditions and the others as biotransformation metabolites such as AFM_1, AFB_{2a}, AFG_{2a}, $AFGM_1$, and AGM_2.[24] The characteristics of climate and poor hygienic storage conditions in some regions of Asia result in a high incidence of AF contamination in a wide range of food and feed.

In East Asia, a report in China indicated that fermented bean sauces have a high exposure risk of AFB_1, and the contamination level varies significantly according to different production channels. For example, the content of AFB_1 in homemade bean sauce samples (1.26−16.41 μg/kg) was higher than that in workshop and factory samples (1.35−8.67 μg/kg). The contamination difference between the samples was wide, and some samples exceeded the maximum allowable level of commercial fermented bean paste (5 μg/kg).[25] Therefore, environmental hygiene in the production process may be the main reason for the difference of mycotoxin contamination in bean sauce samples. A study by Zhao et al.[26] conducted in China from 2018 to 2020 found that the average levels of AFB_1 in feedstuff and complete feeds were 1.2−27.4 μg/kg, and the incidence was 81.9−100%, with 0.9% of raw feed ingredients contaminated by AFB_1 exceeding the Chinese safety standard concentration. Notably, the maximum value of AFB_1 contamination in corn was significantly different in different years. For example, it was 221.0 μg/kg in 2018 and 2019 but 11.8 μg/kg in 2020. These are also far from the average level of 4.0 μg/kg. These differences may be due to the fact that the feed samples were obtained randomly from different regions with different environmental factors during harvest, such as substantially higher temperatures and humidity in southern regions than in northern regions.

In Japan, from 2010 to 2015, the detected rate of AFB_1 contamination in corn, soybean meal, and formula feed was 46%, 30%, and 47%, respectively. Through the observation of the mean level of AFB_1 contamination in the formula feed and corn, it was possible that the AFB_1 contamination of corn ingredients passed to the feed as contamination amounts were relatable among both commodities.[27] Mycotoxin-producing fungi can survive during storage under natural conditions in Japan, and the lower rainfall, and higher temperatures may cause a higher concentration of AFB_1. It is important to apply suitable storage conditions to prevent mycotoxin contamination in food and feed.

In South Asia, there has been a significant prevalence of mycotoxin contamination in food and feed. For the poultry industry in Pakistan, mycotoxicosis has been the second most serious problem in breeding because of the contamination of feed. AFB_1 concentrations in all feeds before storage were generally significantly lower than after storage.[28] Aside from the hot and humid climate in Pakistan, poor management and hygiene of poultry feed storage may also contribute to AF infection. In an assessment of aflatoxin contamination in dairy animal concentrate feed in India, 59% of samples were found positive for AFs of the 189 tested samples, while 44% of samples were detected with total AF levels higher than the tolerance limit of 20 μg/kg established by the Food and Drug Administration (FDA). 58% of samples were detected with AFB_1 levels above the European Commission (EC) legal limit of 5 μg/kg.[29] The high incidence of AFs in feed may be related to the contamination of feed raw materials, especially cereals. Aflatoxin levels in the feed component not only have a direct impact on animals but also contaminate their dairy products. Consequently, in addition to continuous monitoring of aflatoxin in feed, it is also necessary to monitor the source of contaminants and to regulate and control the degree of contamination of feed components.

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Table 1. Examples of AF Occurrence in Food and Feed[a]

country	type of AFs	agricultural product/food staff	concentration range (μg/kg)	maximum allowable level (μg/kg; data from national authorities)	reference
China	AFB_1	corn in feed	221.0 (maximum)	50	26
			4.0 (mean)		
		complete pig feed	59.7 (maximum)	10	
			4.1 (mean)		
		complete poultry feed	57.4 (maximum)	10	
			4.9 (mean)		
	AFB_1	wheat	0.04−0.12	5	31
		crackers	0.03−0.10	5	
	AFB_1	bean sauces (homemade)	1.26−16.41	5	25
		bean sauces (workshops)	1.35−8.67		
		bean sauces (factories)	ND ∼ 6.79		
	AFM_1	ultra heat treatment milk	ND-0.0735	0.5	32
		pasteurized milk	ND-0.15367		
Japan	AFB_1	corn	24 (maximum)	10	27
		soybean meal	6.7 (maximum)	10	
		formula feed	20 (maximum)		
South Korea	AFs	soybean food (meju)	0.2−48.3	15	33
		soybean paste	0.88−16.17	15	
	AFB_1	millet	0.4−5.6	10	34
		sorghum	0.7−1.7	10	
		mixed cereal	0.7−12.4	10	
	AFB_1	soybean food (meju)	0.6−21.4	10	33
		soybean paste	1.06−15.25	10	
Thailand	AFs	animal feeds	4−38.70	20	35
		chia seeds	0.4−10.99	4 (EU)	36
	AFB_1	liver (free grazing ducks)	1.60 (average)	20	37
			3.04 (maximum)		
		intestine (free grazing ducks)	1.31 (average)	20	
			1.73 (maximum)		
		egg yolk (free grazing ducks)	1.87 (average)	20	
			4.56 (maximum)		
Pakistan	AFs	dried apricot	0.31−11.11	4	38
		dried mulberry	1.36−2.22	4	
		dried figs (injeer)	0.69−3.44	4	
	AFB_1	roasted peanuts	16−98	10	39
	AFM_1	raw milk	0.48−0.85	0.5	
	AFB_1	salty peanuts	15−85	10	
	AFB_1	raw peanuts	22−85	10	
Iran	AFB_1	pistachio	1.14 (mean)	2	40
	AFB_1	edible oils	0.2−0.4	30	41
	AFM_1	pasteurized liquid and powdered milk product	0.05−3.31		42
	AFM_1	pasteurized milk	40.6−84 ng/L	0.5	43
		sterilized milk	30.9−89.3 ng/L	0.5	
		breast milk	3.3−7.7 ng/L	0.5	
	AFM_1	cheeses	0.05−0.42	0.25	44
Turkey	AFB_1	baby food	0.01−0.08	0.1	45
	AFB_1	raw hazelnut kernel	0.09−10.6	5	46
		roasted hazelnut kernels	0.17−9.59	5	
		dried figs	0.1−12.5	2	
	AFs	raw hazelnut kernel	0.09−11.3	10	
		roasted hazelnut kernels	0.17−11.2	10	
		dried figs	0.1−28.2	4	
	AFB_1	figs in 2017 harvest year	64−6220		30
		figs in 2018 harvest year	2−22 300		
	AFG_1	figs in 2017 harvest year	80−6630		
		figs in 2018 harvest year	1−24 600		
	AFM_1	dried figs	1−2730		
	AFs	chocolate products	0.15−2.04		47
	AFM_1	raw milk	0.005−0.08	0.05	48

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Table 1. continued

country	type of AFs	agricultural product/food staff	concentration range (μg/kg)	maximum allowable level (μg/kg; data from national authorities)	reference
		ezine cheese	0.02−0.16	0.5	
		cheese halva	0.05−0.21	0.5	
India	AFB_1	dairy animal concentrate feed	2.8−374.6	5 (EC)	29
	AFM_1	pasteurized milk	0.027−2.281	0.5	49
	AFs	single discolored kernels whole groundnut products	7−1 383 400	10	50
		pool discolored kernels whole groundnut products	142−357 300	10	
		dairy animal concentrate feed	3.5−406.1	20 (FDA)	29
Lebanon	AFB_1	wheat	1.05−7.36	2	51
Sri Lanka	AFs	edible vegetable oils	2.25−72.70	4	52
	AFB_1	edible vegetable oils	1.76−60.92	2	
Indonesia	AFB_1	maize	0.3−6171		9
		peanut	0−357		
		dried chilies	39.3−139.5		53
	AFB_2	dried chilies	2.6−33.3		
Malaysia	AFB_1	raw peanut kernels	<LOD to 995.4		54
		peanut-based products	<LOD to 196.7		
	AFs	raw peanut kernels	<LOD to 1021.4	15 (EC)	
		peanut-based products	<LOD to 247.7	10 (EC)	
Saudi Arabia	AFB_1	rice	0.014−0.123		55
	AFs	rice	0.052−2.58	20	

[a]ND: Not detected. LOD: Limit of detection.

In West Asia, Turkey is one of the world's top fig exporters. Figs are susceptible to AF contamination because of their characteristics. Thus, it is extremely crucial to investigate AFs in figs. Between 2017 and 2018, Sulyok et al.[30] identified 180 samples of Turkish dried figs and reported the contaminated fig levels of AFB_1 ranged from 64 to 6220 μg/kg in 2017, while it ran from 2 to 22 300 μg/kg in 2018. These differences between each year are influenced by many factors, especially climatic conditions such as drought. Notably, compared to the natually occurring aflatoxin, AFM_1 is a metabolite after biotransformation. It is the first time that AFM_1 (1−2,730 μg/kg) has been reported to naturally exist in dried figs. This result suggests that AFB_1 can be transformed to AFM_1 in food.

The occurrences of AFs in different Asian countries are summarized in Table 1.

3.1.2. The Contamination of OTA in Food and Feed. OTA is a major mycotoxin produced by several fungal species of *Penicillium* and *Aspergillus* genera. The structure of OTA is a *p*-chlorophenol group containing a dihydroiso-coumarin portion bound to L-phenylalanine amide, which is known as a bioactive extrolite from secondary metabolism.[56,57] According to previous studies, there is a wide range of toxicological effects for OTA, including nephrotoxicity, teratogenicity, and immunotoxicity.[58−60]

In East Asia, a large range of grains and dry fruits are contaminated by OTA. Research about the OTA level in maize in China indicated that 2.5% of samples were detected to be positive for OTA in maize and maize-derived food with a mean concentration of 10.3 μg/kg, which exceeded the maximum permitted level in China.[19] A report about dry fruits showed the presence of OTA in the raisin samples, but the percentage exceeding the limit value (5 μg/kg) was low. The proportion of samples positive to OTA is below 10% (6.7%) with a concentration range of 4.6−7.4 μg/kg.[61] The effort to inhibit foods contaminated with OTA from escaping into the market contributes to the low occurrence of OTA in food commodities.

South Korea follows traditional food and prevention procedures to prevent OTA contamination, which plays an important role in avoiding food losses. The test on 100 meju samples showed half of the samples were positive for OTA with a concentration range from 0.1 μg/kg to 193.2 μg/kg. In soybean paste samples, the percentage of samples contaminated with 0.88−26.29 μg/kg of OTA is 48.9%. About 22.73% of 22 positive soybean pastes were contaminated with concentrations exceeding permissible limits for OTA set by the KFDA (20 μg/kg).[36] As traditional condiments, soybean pastes and soy sauce are popular in South Korea. Therefore, continued control of OTAs is warranted to ensure public health.

In South Asia, the OTA contamination level in various food matrices was analyzed. In 2018, 320 samples of edible nuts and dried fruits were investigated in the major cities of Punjab, Pakistan. 5% of raisin samples were analyzed to be positive for OTA with a mean concentration of 5.60 μg/kg. Only four samples of edible nuts and dried fruits were contaminated with a concentration above the maximum limit recommended by the European Union (10 μg/kg).[62] However, contamination of maize grains with OTA was fairly high in the maize samples in Pakistan. OTA was detected in 71% of maize samples ranging from 2.14 to 214 μg/kg in 2020 and 61% of grain samples ranging from 1.41 to 53.9 μg/kg in 2022.[63,64]

The contamination of OTA in feed impacts animal health and triggers public health issues. In West Asia, research in Jordan indicated that about 38.5% of feed is contaminated by OTA, with an average concentration range from 2.64 μg/kg to 3.16 μg/kg in the poultry industry. It is worth noting that the increasing level of OTA in feed would result in greater deposition of mycotoxin in animal tissues. 66% of poultry breast samples and 100% of leg and thigh samples collected from Jordan contain OTA.[65] In Iran, in 2018, the risk

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Table 2. Examples of OTA Occurrence in Food and Feed

country	agricultural product/food staff	concentration level range (μg/kg)[a]	maximum permitted level (μg/kg; data from national authorities)	reference
China	raisins	4.6−7.4	5	61
	maize and maize-derived food	10.3 ± 5.71 (mean ± SD)	5	19
Vietnam	roasted coffee	0.75 (mean)	5 (EC)	66
Thailand	roasted coffee	0.17 (mean)	5 (EC)	
	instant coffee	2.19 (mean)	10 (EC)	
South Korea	meju	0.1−193.2	20	36
	soybean paste	0.88−26.29	20	
Pakistan	maize	2.14−214	5	63
	maize grains	1.41−53.9	5	64
	raisins	5.60 (mean)	10	62
	dried apricots	3.10 (mean)	10	
	figs	2.10 (mean)	10	
The Hashemite Kingdom of Jordan	feed	1.72−3.70		65
	corn feed	1.54−3.18	5	
	thigh and leg	1.90−2.98		
	liver	4.06−7.68		
	gizzard	1.89−2.26		
	breast	2.81−3.31		
Iran	pistachio	0.413 (mean)	5	32
	grape juice	0.14−2.69	2	67
	coffee	0.48−2.69	10	68
Turkey	chocolate products	0.18−0.75		49
	packed red pepper flake	0.6−1	15	69
	unpacked red pepper flake	1.1−31.7	15	
	baby food	0.06−0.07	0.5	70
Lebanon	wheat samples collected from warehouse A	1.05−7.36	3	50
	wheat samples collected from warehouse B	1.01−7.31	3	
Cambodia	coffee beans	0.19−1.12		71
Indonesia	dried chilies	23.7−84.6		53
Philippines	coffee in the drying yard	4.17−514.46		72
	stored green coffee beans	3.04−461.09		
	roasted coffee samples	3.03−7.57	5	

[a]SD: Standard deviation.

assessment results of two mycotoxin levels in five commercial pistachio varieties indicated that the mean OTA level of 0.413 μg/kg was lower than the maximum limit of 5 μg/kg prescribed by EC regulations.[32]

The occurrences of OTA in different Asian countries are summarized in Table 2.

3.1.3. The Contamination of ZEN in Food and Feed. ZEN is a mycotoxin produced mainly by the *Fusarium* genera, which contaminates food and feed stuff worldwide, particularly cereals like corn and wheat. There is evidence that ZEN has reproductive and developmental toxicity, carcinogenicity, genotoxicity, and immunotoxicity.[73]

In East Asia, Hong et al.[74] reported ZEN contamination in samples of cereal and their products in China. The result indicated that the ZEN positive rate was 62.6%, which ranged from 2.7 to 867.0 μg/kg, and 6.0% samples were over the limit levels. In 2018−2020, 2089 feed stuff samples and 1415 complete feed samples were collected in China for ZEN analysis. The results showed that 96.9−100% of samples were contaminated by ZEN, with the mean concentrations ranging from 48.1 to 326.8 μg/kg; 0.5% feed stuff and 1.9% complete feed samples were contaminated with ZEN, exceeding the Chinese safety standard concentration level. 2.9% of pig feed was found to be contaminated above the prescribed ZEN limit.[26] Although this result was much lower than previous data, complete feeds for pigs still had the highest occurrence of a ZEN contamination level in complete feeds. Notably, the contamination origin could be due to the contamination of the cereal component, including corn, wheat bran, and corn gluten meal. The raw materials could be seriously contaminated with more than one mycotoxin, resulting in mycotoxin cocontamination and exertion of synergistic toxic effects.

There were five types of cereal grain samples collected in South Korea for analyzing the level of mycotoxins in cereal grain in 2017. The contamination level of ZEN, 0.9−313 μg/kg, in sorghum samples was higher than that in the other four types of cereal grain samples. With the highest incidence (62%) for ZEN, sorghum samples contained ZEN exceeding the maximum level of 200 μg/kg set by KDFA.[37] These differences may be due to different sampling areas during harvest, different weather conditions, and differences in grain varieties. Based on the highest incidence, monitoring ZEN during harvest in cereal grains (especially for sorghum) is essential to minimizing public health risks.

In Thailand, ZEN was detected in samples of seven different varieties of rice in 2019. The incidence of ZEN in rice samples was 50%. ZEN was detected in riceberry rice samples, with the highest incidence being 46.67%. Only 3.33% of jasmine rice

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Table 3. Examples of ZEN Occurrence in Food and Feed

country	agricultural product/food staff	concentration level range (μg/kg)	maximum permitted level (μg/kg; data from national authorities)	reference
China	cereal and cereal products	2.7−867	60	74
	corn and its byproducts (except corn bran and corn steep powder)	90.3 (mean)	500	26
		822.0 (maximum)		
	corn bran	145.4 (mean)	1500	
		742.6 (maximum)		
	soybean meal in feed	81.7 (mean)	1000	
		522.0 (maximum)		
	complete feed for young pigs	81.5 (mean)	100 (for young gilts)	
		1,599.0 (maximum)	150 (for young pigs)	
			250 (other complete feeds for pigs)	
	complete poultry feed	108.0 (mean)	500	
		852.8 (maximum)		
	complete ruminant feed	98.2 (mean)	500 (concentrate supplement for calf, lamb, and lactation period)	
		906.9 (maximum)	500 (other complete feeds)	
Thailand	white rice	60.91 (mean)	100	75
	jasmine rice	60.42 (mean)	100	
	Japanese rice	58.55 (mean)	100	
	white sticky rice	92.79 (mean)	100	
	GABA brown rice	67.94 (mean)	100	
	black sticky rice	54.13 (mean)	100	
	riceberry rice	71.94 (mean)	100	
	animal feeds	25.10−879.60	100	38
South Korea	brown rice	0.4−37.6	200	37
	millet	0.7−61.5	200	
	sorghum	0.9−313.0	200	
	maize	0.9−14.7	200	
	mixed cereal	0.2−36.0	200	
Japan	corn	46 (mean)	1000	76

and Japanese rice samples were contaminated by ZEN. The concentration level for ZEN in tested samples was all below maximum regulatory limits, which means the risk of exposure to ZEN is not alarming to public safety in the region.[75] However, ZEN contamination in animal feeds is prevalent in Thailand. Research of mycotoxin contamination in animal feed in Thailand from 2015 to 2020 showed that ZEN had the highest contamination rate of nearly 50%, especially in rice bran, soybeans, and "unclassified ingredient" samples.[38]

The occurrences of ZEN in different Asian countries are summarized in Table 3.

3.1.4. The Contamination of DON in Food and Feed. Deoxynivalenol (DON) is an agriculturally significant mycotoxin mainly produced by certain *Fusarium* species, which frequently infect grains, such as corn, wheat, and rice.[77] Exposure to DON contamination poses serious risks to public health.

In 2019, a reported case from a primary school in Zhuhai, China demonstrated that some students had nausea and vomiting after breakfast. On investigation, DON was detected in leftover raw noodles with a concentration ranging from 6856 to 11 982 μg/kg. The concentration of DON in leftover cooked noodles ranged from 878.3 to 1074.2 μg/kg, which was taken by the students.[78] DON and its acetylated derivatives were detected in different cereal grains harvested widely in China. According to the results of the determination of DON in wheat samples from Northwest China in 2013, the frequency of DON contamination was 82.8%, and 10% of the DON content exceeded the Chinese regulatory limit (1000 μg/kg).[34] Another research conducted in 2020 also showed a high contamination frequency. All wheat samples were detected as positive for DON, and 99.83% of maize samples were positive for DON. The mean concentration for positive wheat samples and positive maize samples was 165.87 μg/kg and 175.30 μg/kg, respectively.[79] In the same year, rice samples from Jiangsu Province of China were collected to analyze for mycotoxins, and 30.9% of rice samples were positive for DON with a concentration range from 8.8 μg/kg to 19 145 μg/kg. In positive rice samples, the concentration of 11 samples (4.7%) contained a level of DON above the maximum regulatory level.[80] In short, the proportion of samples positive to DON in cereal grains was high, but relatively few of the positive samples exceeded the regulated maximum level. DON also presents the same problem in feed. According to the research conducted by Zhao et al.,[26] DON occurred in 96.4−100% of feedstuffs and complete feeds, with the average values ranging from 458.0 μg/kg to 1925.4 μg/kg. The maximum contamination of DON was 9186.4 μg/kg in wheat middlings harvested in 2018. Although only 0.1% of analyzed feed ingredients contaminated with DON exceeded China's safety standards, 8.9% of the complete pig feed samples that were contaminated with DON exceeded the Chinese safety standard concentration. It is worth noting that contamination of raw feed materials like wheat middling, which were quite heavily contaminated by DON, could lead to whole feeds being contaminated at levels beyond the limitations.

In South Korea, feed samples and feed ingredient samples were collected between 2009 and 2016 to determine DON contamination level. DON was detected in 95.3% of the compound feed samples, with a range of 0.4 to 2420.0 μg/kg.

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Table 4. Examples of DON Occurrence in Food and Feed

country	agricultural product/food staff	concentration level range (μg/kg)	maximum permitted level (μg/kg; data from national authorities)	reference
China	cereal and cereal products	6856−11 982	1000	78
	wheat	165.87 (mean)	1000	79
	maize	175.30 (mean)	1000	
	rice	8.8−19 145	1000	80
	corn in feed	629.3 (mean)	5000	26
		3343.6 (maximum)		
	soybean meal in feed	502.3 (mean)	5000	
		1,140.6 (maximum)		
	complete pig feed	661.3 (mean)	1000	
		3,712.2 (maximum)		
	complete poultry feed	660.8 (mean)	3000	
		2,970.1 (maximum)		
	complete ruminant feed	752.1 (mean)	1000 (concentrate supplement for calf, lamb and lactation period)	
		2,613.7 (maximum)	3000 (Other complete feeds)	
Japan	corn	400 (mean)	1000	76
South Korea	feed material (cereals and cereal products with the exception of maize byproducts)	0.01−8480.0	10000	81
	complementary and complete feed stuffs for pigs	231.5 (mean)	900	
Thailand	instant noodles	89 (mean)		82
	bread	4−331		
	animal feeds	0.50−0.70	900	38
Iran	wheat	85.0−540.2		84
	rice and bread	6.0−368.7	1000	85
	positive puffed corn snack	60.2−368.7	1000	
Pakistan	wheat and corn products	50−2050	2000	86
Turkey	baby food	6.32−37.57	200	45
	nut-based products	11.81−42.09		70

It was found in over half of the collected feed ingredient samples (64%), with a range of 0.01 to 8480.0 μg/kg. According to the guidance values of South Korea for DON management, DON should be controlled at 900 μg/kg in supplemental and full feeds for pigs, while for the grain it should be under 10 000 μg/kg. In this study, two compound feed samples out of 160 pig feed samples exceeded the guidance value limits.[81]

In South East Asia, Pralatnet et al.[82] analyzed 50 instant noodle samples and 50 bread samples for DON contamination in Thailand. The DON occurrence in instant noodles was less than that in bread. The positive rate of DON is 40%. The concentrations of DON in tested samples were all below the maximum level in regulation, which suggested a low DON exposure risk via noodles and bread in urban areas of Thailand. This result is consistent with the conclusions of previous research by Poapolathep et al.[83]

In West Asia, 150 wheat samples from Kermanshah Province in western Iran were analyzed. The DON level for these samples ranged from 85.0 μg/kg to 540.2 μg/kg. The concentration of DON increase during the wheat dough fermentation due to DON precursors converted to DON with the presence of yeast.[84]

The occurrences of DON in different Asian countries are summarized in Table 4.

3.1.5. The Contamination of Fumonisins in Food and Feed. Fumonisins are global contaminants of corn and other cereals, produced by the fungus *Fusarium verticillioides* and the closely related *Fusarium proliferatum*. Fumonisins are related to several health issues all around the world, such as esophagus cancer.[87] According to the 2017 Biomin World Mycotoxin Survey, fumonisins have occurred in various parts of Asia with 85% incidence.[88]

Maize is one of the most important staple food crops in East Asia. Some studies have reported that contamination of maize with fumonisins is frequently occurring in certain areas of China. In 2018, Li et al.[89] detected the contents of the fumonisin B_1 (FB_1) and fumonisin B_2 (FB_2) in maize kernels. They found that a total of 57.1% of all maize samples were contaminated with fumonisins, from ND to 10.1 μg/g. A study investigated the occurrence of fumonisin in corn-based food products from Shandong Province, China. The results showed that the occurrence of FB_1 (94.4%), FB_2 (78.9%), and FB_3 (92.2%) is very frequent with mean levels of 128.2 μg/kg, 9.84 μg/kg, and 5.48 μg/kg, respectively. China has no maximum limits for fumonisins in foods or feed yet, but a few samples exceeded the maximum limits of 800 μg/kg according to European regulations, which indicates the need for more continuous and strict control.[90]

A study in Japan conducted by Uegaki and Tsunoda[91] on assessing the mycotoxin concentration in Japanese domestically produced feed found that the maximum concentration of FB_1 varied in different production areas. In Kanto, the maximum concentration of FB_1 in corn feeds was 2400 μg/kg, which is higher than in other regions. In general, the difference is related to regional differences in climate, human farming, and crop transportation.

A South Korean study of the simultaneous determination of multiple mycotoxins in five commercially available grains found that the levels of FB_1 and FB_2 contamination were similar in the same grain group but varied greatly among different grains. Fumonisins detected in maize (1.9−2990 μg/

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Table 5. Examples of Fumonisins Occurrence in Food and Feed

country	type of fumonisins	agricultural product/food staff	concentration range (μg/kg)	maximum allowable level (μg/kg; data from national authorities)	reference
China	FB_1	maize kernel	ND-5400		89
	FB_2	maize kernel	ND-4700		
	FB_1+FB_2	maize kernel	ND-10100	4000 (EC)	
	FB_1	corn-based food	4.16−1775		90
			128.2 (mean)		
	FB_2	corn-based food	0.12−141.6		
			9.84 (mean)		
	FB_3	corn-based food	0.10−70.64		
			5.48 (mean)		
	FB_1	commercial pet foods	6.6−191.9		96
Japan	FB_1	corn feed	ND-2400		91
		grass feed	ND-850		
South Korea	FB_1	brown rice	2.1−22.8	4000	92
		millet	2.0−32.6	4000	
		sorghum	5.8−890.0	4000	
		maize	3.8−2990.0	4000	
		mixed cereal	3.1−80.1	4000	
	FB_2	brown rice	1.6−18.8	4000	
		millet	1.6−31.1	4000	
		sorghum	4.0−223.5	4000	
		maize	1.9−620.0	4000	
		mixed cereal	1.8−22.1	4000	
Pakistan	FB_1	wheat and barley products	ND to 980.5 ± 211.4	200	93
	FB_1	rice	100−400		94
	FB_2	rice	100−400		
	FB_3	rice	125−500		
	FB_1	poultry feed	205 (median)		95
Turkey	FB_1	cereal-based foods intended for infants and toddlers	42.5−100.9	200(EC)	97
Indonesia and Iraq	FB_1	maize	20−1290	4000(EC)	98

kg) and sorghum (42.8−160.8 μg/kg) are higher compared to those in other types of cereal grains. However, none of the samples exceeded the maximum limit (4000 μg/kg).[92]

In South Asia, several studies in Pakistan reported the widespread presence of FB_1 in food and feed. The positive rate of FB_1 in wheat, barley, and flour samples was 90%, and that in rice samples was 42%.[93,94] Meanwhile, a study on feed also found a high rate of mycotoxin occurrence, and all poultry feed samples in the study were contaminated with FB_1.[95]

The occurrences of fumonisins in different Asian countries are summarized in Table 5.

3.2. Mycotoxin Contamination in Different Regions of Asia.

Since different countries vary in economy, regulations, geographic location, climate, and other factors, there are different levels of mycotoxin contamination in food import and export trade. The Rapid Alert System for Food and Feed (RASFF) is the European Union's rapid early warning system, crisis management, and emergency response mechanism for food and feed. To some extent, RASFF can monitor the quality and safety situation of food exported from Asian countries to the EU. The analysis of mycotoxin contamination data from the early warning system can provide a reference for improving food safety and quality in Asian countries.

From January 2021 to March 2022, RASFF noted 290 cases of serious risk of mycotoxins in food and feed in Asia, including 11 countries: Azerbaijan, China, India, Iran, Lebanon, Pakistan, Sri Lanka, Turkey, Uzbekistan, Vietnam, and Georgia. Of these, 114 were reported to Turkey, 53 to Iran, and 34 to India. AFs and OTA are the main mycotoxins in the RASFF notification on food and feed in Asia. The category mainly includes nuts, nut products, seeds, dried fruits and vegetables, herbs, and spices. According to RSAFF data, all food found contaminated belongs to developing Asian countries. Considering environmental, cultural, and economic factors in underdeveloped countries, agricultural products contaminated by mycotoxin have always been a public health problem and need keen attention.

Turkey is the country most frequently notified by RASFF, and its mycotoxin risk mainly involves AFs and OTA pollution of dried fruits and nuts. In the food category, the reported cases of dried figs account for the highest proportion, which should be highly valued. Turkey's humid maritime climate, warm and dry, coupled with long-term sunshine, is very conducive to the growth of the fig tree (*Ficus carica* L). However, subtropical and temperate climatic conditions make *F. carica* fruit easily polluted by filamentous fungi in the field growth, ripening, and drying stages.[46]

In Iran, 50 cases (94%) of mycotoxin warnings are related to AFs in pistachios, and the other three cases (6%) are also related to nuts and seeds. During the planting period, factors such as the area of cultivation, traditional harvesting techniques, weather conditions, and plant protection measures may have an impact on pistachio contamination by mycotoxins. During storage, water activity (a_w) and temperature are crucial for fungus growth and AF production.[99]

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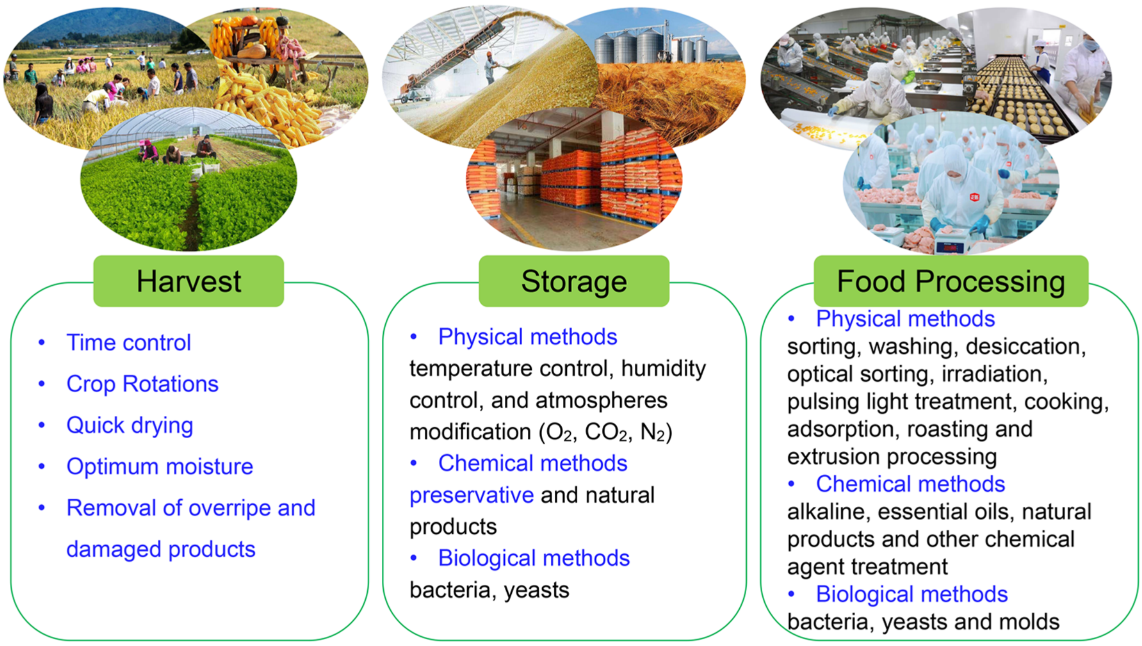

Figure 1. Mycotoxins prevention and control strategies in the process of harvest, storage, and processing.

The categories of food and feed noted by RASFF in India are more diverse, including nuts, nut products, seeds, fruits, vegetables, cereals, bakery products, feed materials, herbs, and spices, and mycotoxin contamination is 91% AFB_1 and 9% OTA. The main climate type of India is the tropical monsoon climate, which is characterized by high temperatures throughout the year, with obvious rainy and dry seasons, which is beneficial to the growth and toxin production of *A. flavus*. Many factors also have impacts on mycotoxin contamination in India, such as unhygienic surroundings, a lack of sanitation facilities, poverty, and poor supervision of the food production chain and food system.[10,100] It is worth noting that different standards of mycotoxin contamination limits between trading countries will also have an impact on international trade. According to the latest revised food safety and standard regulations issued by the Food Safety and Standards Authority of India (FSSAI), the limited level of AFB_1 and AFs in cereal and cereal products, nuts, and oil seeds is 10 μg/kg and 15 μg/kg, respectively.[101] However, the EU has stricter limits for AFs. Based on the regulatory standards for the concentration of mycotoxins in agricultural products and foodstuffs in the EU, the permission level is 2 μg/kg for AFB_1 and 4 μg/kg for total AFs, respectively.[102] In view of the great attention paid to mycotoxins in the import and export of food and feed, the following suggestions are helpful for reducing the impact and losses caused by mycotoxin pollution: First, fully follow the regulatory requirements of exporting countries on food and feed, with awareness about the new regulatory trends; respond in time, and gradually establish a complete regulatory response mechanism. The second is to improve the research on product quality risk characteristics, carry out risk management on products that are often noted, improve the planting environment, and increase the research investment of antifungal varieties in laboratory and practice. The third is to improve quality control. The country of origin of raw materials needs to strengthen the supervision of the production chain and product inspection, implement good production norms, and establish an effective quality management system. The processing country needs to control the procurement of raw materials, strengthen supervision in storage and transportation, and conduct inspections before export.

3.3. Prevention and Control Strategies. This systematic review of the scientific literature on mycotoxin contamination in food and feed in Asia in recent years reveals that mycotoxin contamination is widespread, especially in developing and tropical countries. Although many countries have taken active preventive measures and instituted control strategies, and most mycotoxin contamination has been controlled within the prescribed range, the economic and public health problems caused by mycotoxins in Asia still need attention and cannot be ignored.

Previous studies have shown that the contamination level of mycotoxins in food and feed is correlated with many factors, including (a) food species/feed types, such as susceptibility to mold infection, water content, and composition ratio; (b) environmental factors, such as soil, climate, temperature, and humidity; (c) food processing, such as sorting, washing, and cooking; and (d) preservatives, such as chemical agents, essential oils (EOs), and natural antioxidants.[8]

Figure 1 summarizes mycotoxin prevention and control strategies in the process of harvesting, storage, and processing, which can be effectively applied to the control of mycotoxin contamination in Asia. In general, preventing mycotoxin production in the field (preharvest) and controlling contamination in storage (postharvest) are the most effective ways to reduce mycotoxin levels in food and feed.

In order to reduce mycotoxin contamination levels, strategies to reduce mycotoxin contamination from preharvest to postharvest mainly focus on inhibition of fungal contamination, such as using fungicides, controlling temperature and humidity, using preservatives, and modifying atmospheres.[103,104] A study involving 63 small holder dairy farms in Thailand was conducted to determine the contamination of AFB_1 when keeping various dairy feeds in a farm environment.[8] The result demonstrated that the

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concentrations of AFB_1 in all feeds increased after storage, but the increasing ratio of each feed type is different because of mechanical and chemical compositions such as moisture contents. In addition, feed storage management and environmental conditions can promote mold growth and toxin production.[8] Although the geographical and climatic conditions of each country are different, mycotoxin contamination can be effectively controlled by adjusting feed composition, temperature, and humidity. In addition, modified atmosphere storage, such as modifying O_2 and CO_2 and the use of N_2, has been studied for storing wet grains, especially for animal feed.[103] It can also improve the disease resistance of products, for example, by creating varieties resistant to fungi.[104] Rice is a staple food consumed in China, but due to the high temperature and humidity in southern China, infection-resistant rice breeding of mycotoxigenic fungal species could be an effective method to improve the safety of rice in China.[11] Direct degradation of accumulated toxins is also a strategy for controlling mycotoxin contamination. It can be divided into three main categories: biological detoxification, mycotoxin binders, and herbal products for the amelioration of toxic effects of mycotoxins. Among them, biological detoxification, including mycotoxin modifiers (bacteria, fungi and yeast) and enzymes, was extensively studied.[105]

In fact, it is difficult to completely prevent mycotoxin contamination in raw materials during early harvesting and storage. Therefore, food processing also plays a vital role in preventing and controlling mycotoxin in food and feed. It has been reported that various strategies have been developed to reduce mycotoxin contamination levels in food processing, including physical, chemical, and biological methods.[106] Physical methods of mycotoxin control can be varied, starting with simple methods, such as crop sorting and washing, food processing and cooking, etc. The advantage of these methods is their simplicity, but their ability to inhibit toxins is limited. Studies found that up to 91% of mycotoxins could be removed by simply cleaning maize grains.[106,107] The complexity includes the application of irradiation, such as gamma (ionizing), UV, and microwave radiation, which has the advantage of having less of an effect on the morphology of food and can handle processed food such as bread. However, irradiation may also have a negative effect on crop quality, for example, by inhibiting the germination rate of barley grains.[108,109] Chemical treatment mainly includes alkaline and other chemical agent treatment.[110] Chemical techniques can effectively destroy the structure of mycotoxins. However, since chemically treated products might involve harmful chemicals, it is necessary to evaluate the quality and safety of the products' considered biosafety.[111] Biological control of mycotoxin uses a variety of microorganisms, including bacteria, yeasts, and molds, to control the growth of mycotoxin-producing fungi.[105] Compared to physical and chemical treatment, biology-based detoxification methods are widely considered as environmentally friendly methods with great practical application. For example, the level of AFs in wheat flour was significantly reduced after the introduction of lactic acid bacteria into the bread making process.[112]

In addition to the main traditional methods, EOs and natural antioxidants have been widely studied for their role in inhibiting fungal growth and toxicity in food due to their high efficiency, safety, and wide availability.[113−117] EOs are widely used in the food industry as food preservatives. The ability of EOs to inhibit fungal activity has been demonstrated in many different models. For example, *Zingiber zerumbet* L. essential oil-based chitosan nanoemulsion against AFB_1[118] and sodium alginate-cinnamon essential oil control fungal growth and OTA production.[119] In terms of specific applications, EOs and their nanoformulations are being widely studied and have good application prospects in food storage.[120−122] At present, there are abundant research achievements on natural antioxidants, such as all-trans-β-carotene and other carotenoids extracted from mango peels,[123] piperine extracted from black peppers and long peppers,[124] etc. The natural antioxidants extracted from these agricultural and sideline products are recognized to be safe and feasible in sufficient solvents.

Food safety is intricately linked to people's convention, health, and economic activities. This Review summarizes the current status of major mycotoxin contamination in food and feed in Asia. The overall range of mycotoxin contamination levels in Asian countries from 2016 to 2022 (μg/kg) is shown in Figure 2. Mycotoxin inevitably exists widely in all kinds of

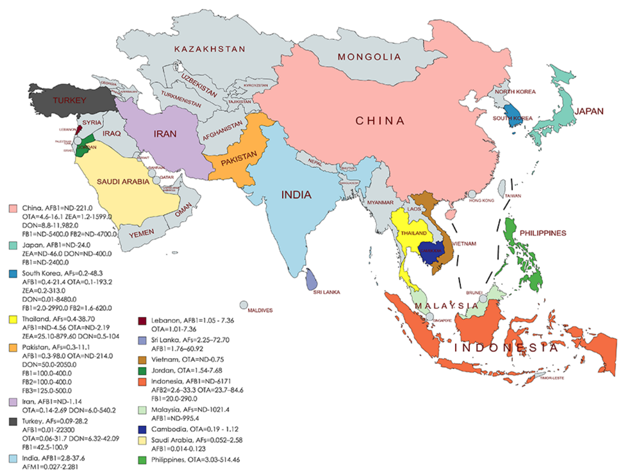

Figure 2. Overall range of mycotoxin contamination levels in Asian countries from 2016 to 2022 (μg/kg)

food and feed commodities, causing huge losses to food safety and economic trade. It can be seen from RASFF notification that specific products are susceptible to mycotoxin contamination, and some developing countries have a greater burden of mycotoxin prevention due to many factors such as geographical location and their own economic situation. There are obvious differences in the supervision, prevention, and control of mycotoxins among different Asian countries. Most Asian countries have strict control regulations, while some countries have poor regulations and high exposure risks. Developed countries in Asia should continue to maintain strict monitoring and establish an effective control system for the whole food production chain, while developing countries should strengthen the prevention and control strategies for mycotoxins.

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