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Mycotoxins in Grains: Toxicological Impact, Detection Strategies, and Public Health Implications

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Abstract

Many types of fungi create mycotoxins, which contaminate cereal grains like wheat, maize, rice, and barley. Even at low doses, aflatoxins, ochratoxins, fumonisins, and deoxynivalenol are harmful to humans and animals. This study covers mycotoxin occurrence, detection, toxicological consequences, and public health concerns in grain-based food systems. Advanced analytical methods, like LC–MS, ELISA, and biosensors, are discussed for their sensitivity and routine monitoring applications. Experimental and epidemiological studies analyze chronic mycotoxin exposure's hepatotoxicity, nephrotoxicity, immunosuppression, and carcinogenicity. Global agencies' regulatory frameworks and safety restrictions are also examined, revealing differences and issues in underdeveloped countries. Finally, to decrease exposure and protect public health, the study stresses the need for coordinated mitigation solutions across the grain supply chain, including preharvest management, postharvest storage, and consumer education.

Keywords: Rain contamination, mycotoxins, food safety, toxicity, detection methods, public health, fungal metabolites

INTRODUCTION TO MYCOTOXINS

Mycotoxins, harmful secondary metabolites generated by various fungal genera, are global food and feed contamination and health issues. Since the discovery of aflatoxins (AFs) in the early 1960s, several mycotoxins, including AFs, ochratoxins (OTs), fumonisins, patulin, zearalenone (ZEN), and trichothecenes, have been detected in food and feed. Most fungi-produced chemicals are harmless to humans. The primary mycotoxins are important because they poison animals and people through food.

Mycotoxins also waste products, increase inspection expenses, and cause handling losses, making them economically important. Mycotoxin contamination of food and feed is a global issue, and even if contaminated raw materials are avoided, compound feeds with infected ingredients will be hazardous. Many international chemical contaminant regulatory lists include mycotoxins with guidance limits due to their importance and potential health effects, and those not covered have national regulatory limits. The handling and storage of grain and grain products and food processing procedures are changed to prevent mycotoxin development. Control tactics require breakthrough technologies for rapid early mycotoxin detection at important food chain control points. Due to their low prevalence in foods, difficulty of detection, resistance to cooking and food processing, and lack of analytical methods to accurately determine contamination levels in many food commodities and complex food matrices and products, methods of contamination remain a food industry concern. Thus, improved analytical methods are needed to give food mycotoxin data, enforce rules, and facilitate worldwide agricultural trade. Mycotoxin kinds, detection methods, toxicity, sources, public health impacts, and mitigation options are covered [1–3].

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TYPES OF MYCOTOXINS

AF, OTs, and Fusarium toxins (fumonisins, trichothecenes, and ZEN) are serious public health concerns [2]. These can cause immediate poisoning, mortality, persistent immunological dysfunction, cancer and infectious agent susceptibility. Their presence in various crops poses a huge food safety and security risk, especially in developing nations [1].

AFs

AFs are very poisonous secondary metabolites generated by a few Aspergillus fungus, including A. A. flavus. parasiticus and *A. nomius*. These carcinogenic, hepatotoxic, teratogenic, and immunotoxic fungus infect wheat, maize, peanuts, and tree nuts, posing major public health risks. Four related compounds—B1, B2, G1, and G2 – are the main naturally occurring AFs. Humans absorb AFs through respiratory, mucosal, and skin contact; inflammatory responses cause major health problems [4].

The main source of AF contamination in staple cereals is preharvest fungal infection; however, it can proliferate postharvest in humid conditions. Because AFs are chemically persistent and cannot be eliminated or blocked by boiling, eating AF-contaminated food can induce acute poisoning and liver cancer. Acute aflatoxicosis epidemics in poor nations have caused liver damage and death in humans and animals. Around the world, chronic subclinical exposure is frequent.

OTs

Penicillium species causes grain OT contamination. The type of crop, development stage, pest damage, and drought affect crop vulnerability [3]. Curvularia directly infects rice and sorghum [5]. Enzymes produced by fungi during grain colonization may reduce grain quality; PPO synthesis is prevalent and helps brown grain. Also, mycotoxins, like deoxynivalenol (DON), impact grain quality.

The risk of OTs from *P. verrucosum* is high in temperate and cold areas. Strong immunosuppressive, mutagenic, carcinogenic, and nephrotoxic mycotoxins [6].

Fusarium Toxins

Maize, wheat, barley, oats, and rice are contaminated by Fusarium toxins, secondary metabolites of fungi. These genera produce nearly 200 species with a variety of toxigenic properties in 25% of the world's crops. About 25 species can produce mycotoxins. Fungi development in the field and during storage can reduce production and quality.

The four groups are trichothecenes, ZENs, fusaric acid, and other poisons. Trichothecenes impede protein synthesis and are cytotoxic. They also decrease antibody production and substantially suppress mononuclear cell immune system development. Animal ZEN mycotoxins contain estrogenic action and can cause precocious sexual development, diminished fertility, abortion, stillbirth, and lower libido. Fusaric acid affects the myocardial, lung, and liver in animals.

Zearalenone

Many Fusarium species synthesize ZEN, a macrocyclic β-resorcyclic acid lactone [7]. Natural contamination of crops, food and feeds occurs worldwide [8]. The USDAs of the US and Canada set quantitative ZEN contamination limits in food and feed. ZEN and its metabolites are estrogenic and may affect animal reproduction.

MYCOTOXIN SOURCES

Mycotoxin generation depends on fungal disease susceptibility, which can occur in the field or during storage. Preharvest contamination of cereal crops is caused by environmental conditions such humidity, temperature, and inoculum levels, as well as insect and mite infestation [3]. Most cereal mycotoxins are generated by Aspergillus, Fusarium, and Penicillium species [2]. Weather is crucial, with DON outbreaks in Hexaploid wheat connected to protracted chilly wet spells. Preharvest, harvest, transport, drying, and storage can all contaminate cereals with mycotoxigenic fungus, but severe contamination usually occurs when crops remain excessively damp (>13.5%) for long periods. Both farmed cereals and wild grass can harbor pathogenic organisms and cause long-term and regional contamination.

Environmental Factors

Cereals and crop-derived pet and farm animal feeds are often contaminated by fungi and mycotoxins. Feeding animals contaminated substances can cause mycotoxins in dairy, meat, and eggs. Worldwide, contamination causes product losses, trade limitations, and health dangers to humans and animals [2]. Climate drives fungal and mycotoxin contamination in grains and crops. Moisture, temperature, crop, and fungi type affect fungal establishment and mycotoxin synthesis. Drought and high CO_2 can significantly impact fungi pathogenicity and food crop mycotoxin contamination. Fertilization and soil type also matter. The important conditions during storage are moisture and temperature. Besides field crop contamination during storage, artificial drying can introduce fungal infection [9]. National and international agriculture, nutrition, and health issues increasingly focus on food safety and security. Preharvest, harvest, and postharvest mycotoxins in grains are a major issue [3].

Agricultural Practices

Geographic location, climate, weather, fungal prevalence, preharvest activities, and postharvest management all contribute to contamination [3]. Toxigenic fungi and their metabolites are typically found in preharvest procedures, which are closely related to the environment. Preharvest contamination is greatly influenced by temperature, humidity, and drought stress. High atmospheric humidity from rainfall or dew, warm temperatures, and prolonged drought stress favor fungal development and AF generation in maize and groundnuts. Contaminated soils, plant detritus, and stray fungi can infect crops during susceptible periods. During droughts, contamination is frequent in India's rain-fed maize crop and postharvest chain [10]. Other preharvest parameters may affect toxin levels include soil temperature, nutrient status, plant temperature, growth stage, plant age, irrigation patterns, plant density, foliar injury, soil moisture, and genetic resistance.

Storage Conditions

Storage Moisture and Temperature

Mold growth and mycotoxin contamination in stored grains rely on moisture and temperature. At 325°C, mold development stops below 0.70 water activity (aw), however species and strain vary [3]. Fusarium molds from naturally infected kaoliang reached maximum colony formation and ZEN production at 26–30°C and 0.96–0.97 aw. A Fusarium strain from Brazilian wheat samples produced DON at 0.92 aw at 25°C and 0.97 at 20–30°C. Many Aspergillus species create AFs at 0.83–0.85 aw at 33°C and 0.94–0.96 at 28°C, depending on the substrate, while OT synthesis begins at 0.85 aw at 20°C [11]. Mold growth in grain piles increases CO_2 levels, which restrict growth at 5% or above. A simulation examined CO_2 generation and dry matter losses from mold growth in deposit siloed maize grains, focusing on AF B1 production.

MYCOTOXIN DETECTION METHODS

Fungi occur throughout the grain production chain and cause spoilage and product losses. Their mycotoxins harm human health. Food companies worry about mycotoxin contamination of cereal grains. Fungal secondary metabolites poison animals acutely and chronically. Cereal mycotoxin detection is crucial, and different approaches are used. Most approaches use chemical or immunological principles. Biosensors are being considered for detecting numerous mycotoxins in grains and derived meals.

Mycotoxins, filamentous fungi's secondary metabolites, damage humans and animals. These natural hazardous chemicals are thermally stable and do not decompose during food preparation or cooking, while heat treatment may lower their toxicity. Drought and wetness increase the risk of fungal crop infection before and after harvest, especially if affected grains are kept improperly. Mycotoxin contamination of food and feed grains harms health and costs the food business a lot of money. Mycotoxin screening and detection start field, postharvest, storage, food processing, and commercial distribution mitigation.

Methods of Chemical Analysis

Many chemical analysis methods are used to manage mycotoxin contamination in grains and derived products. Most quantitative mycotoxin testing in food and feedstuff uses chromatographic methods, including solvent and solid-phase extraction. Immunochemical assays, like ELISA and rmFPIA, are used in food control units because they are sensitive, fast, cheap, and suited for screening large numbers of samples. Instrumental methods for direct or indirect mycotoxin identification are optimized to include shadow imaging, optical sensing, thermal lens spectroscopy, hyperspectral imaging, and laser-induced breakdown spectroscopy [12]. Economically sensitive and selective, spectroscopic approaches can quickly and simultaneously identify single or many mycotoxins in raw materials. Mycotoxin detection has been extensively studied and implemented using optical and spectroscopic methods in recent years due to increased concern about mycotoxin contamination. Direct spectroscopic measurements in the visible or near-infrared bands are employed to determine AFs in cereal grains. Indirect spectroscopic approaches can quantify mycotoxin levels based on fungal hyphae growth, physical or chemical changes in infected grains, or fungi metabolites and byproducts.

Biological Methods

Immunochromatography, immunochemical testing, and ELISA are biological procedures. ELISA uses antibodies to identify and quantify the presence of the molecule of interest by causing a measurable color shift that can be seen compared to a control or measured on a spectrophotometer. Like chromatographic methods, ELISA is sensitive and specific and can be done on-site with little equipment. Immunochromato graphical methods can be modified into easy-to-use test strips like pregnancy or drug addiction tests; many strips with various antibodies can screen for multiple poisons in a sample [13].

New Technologies

Food safety and consumer health depend on rapid and accurate mycotoxin detection [12]. Traditional methods for detecting various mycotoxins in the food supply chain entail extensive sample preparation and expensive equipment operated by expert workers [14]. Thus, fast and effective mycotoxin screening techniques will help producers and regulators make reasonable decisions and avoid disasters. Many successful immunoassays for quick mycotoxin detection have been developed, including ELISA, fluorescence polarization, suspension array, lateral flow, and immunosensors. However, fast toxicological screening for mycotoxin-traces in biological samples is still lacking, limiting mycotoxicosis diagnosis.

MYCOTOXINS' HARM

Mycotoxins are low-concentration fungus (mold) compounds that are very harmful to humans and animals. They pose a major threat to food safety and nutrition. Approximately 25% of crops globally are impacted by mycotoxins. Despite good agricultural and manufacturing procedures, these chemicals threaten food security and safety. Food mycotoxins harm humans, farm animals, and the economy. Governments, agricultural producers and workers, exporters, importers, processors, retailers, and consumers face ongoing challenges. Thus, accurate mycotoxin detection and testing in food and commodities are essential.

Many countries find natural mycotoxins in cereals and cereal-based foods pre- or post-harvest. Naturally occurring mycotoxins such AFs, OT A, ZEN, DON, and fumonisins are important [15]. Aspergillus flavus, parasiticus, ochraceus, verrucosum, and sporotrichioides are the principal sources of these toxins. Other Aspergillus strains produce mycotoxins in lower amounts under different settings. Mycotoxins can cause acute poisoning or persistent disorders. When ingested together, mycotoxins have synergistic effects on biological systems, organs, and tissues.

Aspergillus, Penicillium, and Fusarium molds on food create mycotoxins, which are deadly secondary metabolites [1]. While mycotoxins are usually connected with incorrect grain harvesting, handling, and storage, they can be present in food even when good agricultural and storage standards are followed. Because many mycotoxins are heat- and chemical-resistant, they can survive food processing and cooking. Mycotoxins such as AFs, OTs, fusarium toxins (fumonisins, trichothecenes), and zearalenone (ZEA) affect crops, animal feed, and agriculture [2]. Their prevalence, toxicity, and effects from food processing and storage are known. Most nations set maximum limits or recommended intakes for mycotoxins in food. Mycotoxin regulation, restrictions, and number vary by region. Some countries have made significant institutional attempts to regulate mycotoxins in food. Other countries either have no rules or very high limitations that allow the export of badly contaminated wheat. It is much harder to deal with raw bulk commodities since in most countries, mycotoxin-contaminated items, especially grains, are allowed into the food and feed chain for use and dilution with toxin-free products. This means that infected material is not destroyed or removed but rather mixed with uncontaminated material and introduced into foods without mycotoxin management.

Acute Toxic

A significant, single dose of AFs, OT, fusarium toxins, and zearalenone can cause acute toxicoses in animals and humans [1]. Certain fungi that grow on crops and foods globally create hazardous secondary metabolites called mycotoxins. Aspergillus, Fusarium, Penicillium, and Alternaria fungi can create mycotoxins during crop growth, harvesting, storage, and processing [12]. Mycotoxin refers to many substances with distinct chemical structures [3]. Mycotoxicoses are acute or chronic depending on dose and duration. They may also cause animal cancer, mutation, or teratogens.

Chronic Toxic

Acute or chronic mycotoxins poison humans and animals. AF, OTs, and fusarium toxins were poisonous and carcinogenic [3]. Zearalenone is mostly estrogenic. The most potent and common mycotoxin is AFs. Many mycotoxins have acronyms like M1, B1, G1, etc.

Cancer-Causing Effects

Mycotoxins cause cancer via forming DNA adducts through metabolic activation, not mutational alterations. AF, fumonisins, OT A, T2 toxin, zearalenone, and Penicillium species toxins (sterigmatocystins, verrucolysins) are all suspected carcinogens. AF B 1, the most carcinogenic naturally occurring chemical, causes liver cancer in many animal species, including humans, as a powerful genotoxic and mutagen. Carcinogenic intermediates attach to DNA at the N (7) position of guanine during metabolic conversion, altering the genome and repressing the P53 tumor suppressor gene via a G to T transversion at codon 249. Although Reyes syndrome and infantile cirrhosis have been associated to AF exposure, liver cancer is the most common clinical manifestation. South Africa, China, and Iran link fumonisins to esophageal cancer. Climate, topography, soil composition, and greenhouse gases influence mycotoxin production and may contribute to their carcinogenic consequences. Chemical variables are significant since fertilisers and fungicides can stimulate mycotoxin synthesis, with sublethal dosages of fungicides at specific fungal development stages increasing toxin levels. Not all fungicides increase mycotoxin biosynthesis, depending on environmental conditions. Fungal metabolism and fertilizer components affect mycotoxin biosynthesis, with nitrogen increasing F's 3-acetyl-deoxynivalenol (DON), graminearum. Biological aspects include toxigenic fungi-host substrate interactions, strain variability, and genetic instability [16].

PUBLIC HEALTH IMPACT

Grain mycotoxins cause severe domestic animal toxicoses and chronic mycotoxin exposure for 4.5–5 billion individuals [2]. Cancers include oesophageal and hepatocellular carcinomas, acute toxicoses, child growth impairment, immunological insufficiency, and disrupted nutrient metabolism are the main health issues. Infants, pregnant women, and the chronically ill are especially vulnerable. Multiple experimental and human investigations were used to establish provisional maximum tolerated daily intakes (PMTDI). AFs, OTs, type-B and type-A trichothecenes (medical and colloquially known as vomitoxins), fumonisins, and zearalenone were used to generate chronic and acute reference dosages to assess mycotoxicosis risks. Numerous nations have established mycotoxin limits in foods and feeds to protect people and animal health, but the considerable diversity in worldwide restrictions shows the difficulties of enforcing rules globally.

Mycotoxin Health Risks

Despite substantial food and feed mycotoxin reduction efforts, these dangerous secondary fungal metabolites remain a global public health issue. Chronic exposure to AFs, DON, fumonisins, OT A, and zearalenone, which contaminate food, causes carcinogenesis and a variety of pathologies [15]. Cereals, legumes, spices, dried fruits, nuts, and their processed derivatives can contain mycotoxins [3]. Multiple mycotoxins in food can escalate these health impacts, emphasizing the need for effective mitigation, monitoring, and enforcement. Chemical, biological, and molecular decontamination approaches have been developed to lower mycotoxin levels in field crops, stored grains, and harvested food products.

Populations at Risk

Grain mycotoxins are a major public health issue, especially for vulnerable groups. Higher food consumption relative to body weight and undeveloped organ systems make infants and young children vulnerable to developmental, immunological, and genetic diseases during important developmental windows [17]. Because AFs can pass the placental barrier, maternal mycotoxin consumption harms fetal growth and development. Dietary OT A may harm kidneys and livers in nut-allergic youngsters. Chronic mycotoxin exposure, poor nutrition, and infectious disease co-infection are frequent in immunocompromised and low-income groups [3].

Regulatory Standards

Many nations have set food and feed mycotoxin limits for AF, OT, and CIT [18]. These criteria demonstrate public health concerns about fungus contamination and mycotoxin ingestion [19].

Mycotoxins over legal limits in maize, wheat, and rice can also hinder international trade for several countries. In many underdeveloped nations, especially Africa, food and feed safety requirements are almost nonexistent. Despite comprehensive monitoring in other locations, many foods remain untested or heavily contaminated [3]. Numerous countries monitor AFs, suspected of being Africa's most major fungal toxin. Still, reported values reveal AFs and other metabolites regularly exceed limitations.

Fungal growth and mycotoxin production have long impacted humans, animals, and wildlife. Because some mycotoxins, including AFB1, are carcinogenic and threaten national and global public health, legislation must include thorough quality control and safety assessments.

MYCOTOXINS IN FOOD

Humans and livestock contract mycotoxins from contaminated food, causing disease and economic losses. Mycotoxin-contaminated cereal grains and their byproducts, feeds made from cereal and legume grains, oilseeds, and other protein supplements, milk, dried fruits, nuts, wine, and beer are major sources. In areas where grains are a staple, extensive harvest contamination can harm health and the economy [2].

Mycotoxin-contaminated grain is preferred by producers and consumers globally, with dangerous grain being used as animal feed. Ethiopian research shows widespread ingestion of hazardous grain. Extended testing and public disclosure can raise customer awareness of mycotoxin dangers, giving them an equity-driven incentive to avoid contaminated items and driving suppliers to supply safer goods. Mycotoxigenic fungus on cereal grains can indicate contamination before harvesting [1].

Impact on Food Safety

Many countries' health and economies are threatened by fungus and mycotoxins on food and feed crops [3]. Many fungi produce secondary metabolites, but only a handful are mycotoxins. The main pollutants of cereals globally are AFs, fumonisins, DON (vomitoxin), zearalenone, OT A, and moniliformin. Even while one fungus species can synthesize many mycotoxins, only a few genera produce them.

Consumer Knowledge

Low understanding of mycotoxins and their health dangers emphasizes the need to educate and empower consumers to make safer choices [20]. Despite knowing more about other food-borne dangers, over half of German university students know little about mycotoxins. Some believe pesticides are similarly hazardous, but specialists recognize mycotoxins' long-term carcinogenic consequences. Public education should explain why mycotoxins are dangerous and how simple measures like removing mouldy food and eating a diversified diet limit exposure.

Grain mycotoxin contamination affects human and animal health. Fungi-derived metabolites cause mycotoxicosis and food insecurity in Africa [3]. Fungi reduce nutritional quality and marketability, whereas AFs, fumonisins, DON, zearalenone, OT A, and moniliformin are present at significant amounts. Hillside grain farmers can avoid damage by keeping careful records of rainfall, pesticide programs, insect attacks, and weeds and storing grain properly. A comprehensive approach to grain disease and pest problems would reduce field, storage, and processing toxicity.

WAYS TO MITIGATE

Mycotoxins and their products harm public health. Food safety and consumer awareness are protected by monitoring and regulating standards. Sorting, cleaning, dehulling, and debranning minimize mycotoxins. These procedures work best in Fusarium head blight-exposed cereals. T-2, HT-2, fumonisins, DON, AFs, and DON-3-glucoside can be reduced by cleaning. Fumonisin is traditionally reduced by 40% during cornmeal manufacture. Soaking – plain or acidified – cooking, steaming, and pressure cooking reduce AF content by 34%–70%. Nixtamalization hydrolyses fumonisin ester linkages, reducing tortilla FB1 by 82%. Mycotoxins are mostly eliminated in the steeping and washing fluids and remain water-soluble. Gamma- and electron-beam irradiation degrades trichothecenes better in aqueous media than on maize kernels in situ. Unlike these treatments, bread baking may reduce DON, but studies show no effect. Dough fermentation leaves OTA unaltered and raises DON, which decreases during baking [21].

Management Before Harvest

After vegetative maturity, preharvest begins. This puts grain filling integrity at risk and increases mycotoxin exposure. Mycotoxin release and spore dissemination into vulnerable grains may increase during the prolonged harvest drought.

Preharvest management and mitigation of cereal crop mycotoxins is crucial to reducing their health effects on farmers and consumers [22]. Annual efforts to measure fungal and mycotoxin contamination in cereal crops have made little progress in reducing contamination, especially for food safety.

Several preharvest methods are used worldwide to protect sensitive crops from mycotoxigenic fungus and mycotoxins. Many methods are expensive and complicated. Implementation often depends on the farmer's finances, technology and skill, and future rewards throughout seasonal environmental changes [3]. Climate, geography, production methods, crops, and socioeconomic factors affect preharvest intervention success and mitigation strategy selection.

After-Harvest Habits

Toxicity and treatment efficacy for cereal microbial decontamination and detoxification must be assessed postharvest. Treatment efficiency depends on sample matrix, target organism, moisture content, and water availability, making homogeneous sample treatment difficult. Industrial application requires crop-specific treatment optimization [23]. Even in ideal conditions, a single physical treatment is unlikely to decontaminate and detoxify microbials without affecting grain quality. Using multiple treatments is the best way to get the best results [24].

Food Processing Techniques

Mycotoxins, fungi-produced harmful secondary metabolites, threaten worldwide food safety. Often considered raw material pollutants, food-processing procedures may also be mycotoxin sources.

Cleaning, milling, brewing, fermentation, baking, frying, roasting, flaking, alkaline cooking, nixtamalization, and extrusion lower mycotoxin levels. High-heat procedures decrease mycotoxin according to time and temperature. Mycotoxins, such as DON are more resistant to breakdown, while other products are harder to cleanse.

Biological mycotoxin production during fermentation may detoxify. Release of bound or masked forms from commodities or processing might cause significant postprocessing elevations. Thus, food processing and disinfection require equal attention. Effective food-processing decontamination and detoxification should be irreversible, active against the parent mycotoxin and any modified, masked, or hidden derivatives, nontoxic to humans and/or animals, and preserve nutritional and organoleptic properties, according to. Additionally, only food-safe methods from the production country should be evaluated. This review covers traditional food processing and mycotoxin decontamination [21].

GLOBAL MYCOTOXIN REGULATION PERSPECTIVES

Mycotoxins are a problem on all continents, so regulating their levels in staple foods is crucial for consumer safety. Emergency rules, such as during natural catastrophes, are essential to ensure secure food supplies.

Patulin (PAT), a polyketide mycotoxin generated by Penicillium (particularly expansum), Aspergillus, and Byssochlamys species, often contaminate fruits and processed foods like juice and jams. In 2012, the FDA classified PAT as an adulterant in apple products above 50 µg/kg and published a maximum level of 25 µg/kg in fruit derivatives. However, health concerns from excessive exposure to PAT led other countries to advocate a lower limit of 10 µg/kg. PAT contamination at high concentrations is most likely to occur in foods made from damaged and rotten apples, which are isolated to the raw material [3].

AFs are difuranocoumarins generated by Aspergillus flavus and parasiticus. The class's most poisonous, carcinogenic, and mutagenic congener is AFB1. Although dose–response epidemiological data are lacking, high AF levels, hepatitis B virus infection, and liver cancer (hepatocellular carcinoma) are strongly correlated in humans. AF M1, the main hydroxylated derivative of AFB1 secreted in milk, is mutagenic, carcinogenic, and immunosuppressive like AFB1. Limits of 1 µg/kg in baby meals and milk were set by the European Joint Research Council, as these products impact the most vulnerable population. Essential foods such cereals, durum wheat, maize, rice, corn, and nuts have a maximum of 4 µg/kg, but almonds, pistachios, and dried fruit allow a slightly higher amount.

OTs from Aspergillus and Penicillium species contaminate grains, coffee, cocoa, wine, beer, legumes, and dried fruits. Feed contains them and can spread them to milk and meat. Any of these products can cause acute, chronic, and carcinogenic consequences.

Fusarium species create mycotoxins that contaminate oats, wheat, and maize globally. Fumonisins, tricothecenes, and zearalenone are significant fusarial poisons. Several countries have fusarial toxin laws and guidelines.

Zearalenone, a nonsteroidal estrogenic mycotoxin, is generated by several Fusarium species worldwide, mostly in maize and maize derivatives. Since ZEA mimics 17-β-estradiol, it sequentially attaches to estrogen receptors and promotes the growth of estrogen-responsive cells.

Despite the serious impacts of all the above mycotoxins, global laws are not universal, and country levels can vary substantially, indicating the lack of harmonization even within continents. Mycotoxin levels are only regulated for total AFs and fumonisins in South Africa. Many African countries lack mycotoxin data, which leads to a lack of legislation. These findings highlight the need for greater field research and analytical advancements [25].

Global Standards

Mycotoxins are among the most common natural poisons in foods and feeds and have a global economic impact. Regulations set permissible mycotoxin quantities in food to prevent poisoning. Guidelines vary globally depending on whether the amount is for direct human consumption or animal feeding.

Documented international laws, like Codex Alimentarius Commission regulations, are followed by country-specific regulations [2]. The Codex Alimentarius provides food standards for countries without their own. Most restriction allowances apply to grains, not complete goods. Each nation can follow the Codex norm or set its own higher criteria [26].

Case Studies from Countries

Reports on grain mycotoxin contamination and trade rules have been published. Many countries have regulations to regulate mycotoxin levels in food and feed. However, developing nations still lack this. There is very no information on pre- and post-harvest measures to reduce food mycotoxin levels. Countries regulate mycotoxin limits in different commodities. The International Agency for Research on Cancer classifies AFs and OT A as carcinogens and public health hazards. Mycotoxin limitations in commodities are regulated worldwide.

NEW RESEARCH DIRECTIONS

Next-generation electrochemical platforms based on nanomaterials can improve detection methods' application, sensitivity, specificity, and cost. Thus, a simple, sensitive, accurate, and reproducible electrochemical test for trace level measurement is a desirable current shift. Future solutions may include phasing out existing procedures to make use of their specialization and ease of use and integrating qualified platforms into automation frameworks [2].

Additional research is needed to improve current knowledge on the health effects of mycotoxins in cereals and human food supply, contest the assumptions of chronic, additive, synergistic, and potentiator effects to characterize the overall effects of mycotoxin toxicants, and investigate the interactions between mycotoxins and major viruses, which occur frequently in third-world countries. To completely comprehend the consequences of mycotoxins, it is necessary to establish the molecular pathways responsible for mycotoxin toxicity. Generally, cell-based approaches are effective in providing information on the mechanism of toxicity, but they do not offer an important assessment of the interaction among different tissues, organs, organism compartments, and mycotoxins that simultaneously occur in the real human intake. Multi-omics and toxico-kinetic methods improve mycotoxin toxicity understanding, but more research that considers these pathways are desirable [26].

Novel Detection Methods

Mycotoxins in grains are a global concern due to their possible health and economic effects. Mycotoxin detection technologies are constantly improving, allowing quick monitoring. Next, effective mitigation techniques are evaluated for the field before harvest, warehouse after harvest, and food processing. Food researchers are exploring novel mycotoxin identification methods beyond chromatographic, immunochemical, and spectroscopic.

Mycotoxins are harmful secondary metabolites generated by filamentous fungus such as Aspergillus, Penicillium, Fusarium, Alternaria, and Claviceps. Cereals are the most dangerous diet for humans because they contain Aspergillus, Penicillium, and Fusarium toxins. The molecular and biosynthetic nature of the main families of cereal-contaminating mycotoxins, including the most-studied compounds from Aspergillus, Penicillium, and Fusarium toxins: AFs, OTs, fusarium toxins, and zearalenone. Toxicology is also assessed for these toxin classes.

Understanding Toxicity Mechanisms

Acute symptoms can occur shortly after eating certain food-borne mycotoxins. Some mold metabolites in food cause long-term immune weakness and cancer. Only a few of the hundreds of mycotoxins found in foods are of great concern due to their direct effects on human and animal health. At least 50 Fusarium species create key mycotoxins that contaminate cereal grains like wheat, maize, and millet. Since mycotoxin production is not required for fungal development, fungus must use them to weaken the host to establish and produce harmful secondary metabolites and enzymes.

Mycotoxins are produced and released by environmental factors, but their toxicity depends on the host's vulnerability, defense systems, and metabolic processes. Mycotoxins have been known to have harmful biological effects for decades, but many new toxins, modified metabolites, and diverse biological activities have emerged, making them an important class of chemical contaminants for food chain safety and spurring renewed research into their toxicological mechanisms [15].

CONCLUSIONS

Mycotoxins threaten food safety, security, and public health globally. Filamentous fungi create strong carcinogens and mutagens called mycotoxins. Cereal grains and their products are crucial to human nutrition and exposure to these chemicals, which have been isolated from many meals and feedstuffs. Mycotoxicoses, induced by single or many mycotoxins in the same commodity, are a developing global hazard. Fungi and mycotoxins degrade food quality, nutritional content, marketability, and export potential, causing huge economic losses.

Grain fungi can grow pre-, post-, and during processing and storage under favorable conditions. Preharvest fungal contamination and mycotoxin generation are caused by meteorological, soil fertility, seed quality, plant susceptibility and stress, insect damage, and planting and harvest time. The growing environment during crop growth, flowering, and maturation determines contamination and mycotoxin levels.

The European Commission, Codex Alimentarius, FAO, and WHO monitor mycotoxin globally, however efforts differ regionally and country-by-country. International coordination, communication, and sharing of commercially sensitive information are needed to prevent fungal contamination and mycotoxin production. GAPs and HACCP optimization are crucial tools in mycotoxin protection programs and require collaboration across the value chain from grain production to consumer. Current mycotoxin analyses may underestimate co-occurring mycotoxin exposure, according to empirical findings. More work is needed to defend food safety and security against mycotoxins, which could harm economic development, commerce, poverty reduction, and worldwide human and animal health.

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