Bulletin of Biological and Allied Sciences Research
***ISSN:* 2521-0092**
www.bbasr.org
DOI: https://doi.org/10.64013/bbasr.v2026i1.114
*Bull. Biol. All. Sci. Res., Volume, **11**: 114*
Original Research Article ***Open Access***

FROM TOXICOLOGY TO TECHNOLOGY: HUMAN HEALTH RISKS OF MYCOTOXINS IN THE FOOD CHAIN AND CURRENT APPROACHES TO THEIR DETECTION AND CONTROL

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(Received, 17th January 2025, Accepted 24th January 2026, Published 11th February 2026)

Abstract *Mycotoxins are small secondary metabolites produced by filamentous fungi such as Aspergillus, Fusarium, and Penicillium. They are common contaminants of food and feed and pose a serious threat to public health. These toxins exert acute and chronic effects ranging from hepatotoxic, nephrotoxic, estrogenic, neurotoxic, and immunosuppressive outcomes to mutagenicity and carcinogenicity, with exposure occurring via ingestion, inhalation, and dermal contact. Major classes include aflatoxins, ochratoxin A (OTA), fumonisins, zearalenone (ZEA), trichothecenes, and patulin, frequently contaminating cereals, nuts, spices, dried fruits, juices, and dairy products. Climate change, through drought, heat, and elevated CO_2, is expected to alter fungal growth and raise mycotoxin risks. The burden is highlighted by aflatoxicosis outbreaks, such as the 2004 event in Kenya that caused 125 deaths. Mechanistic studies show that aflatoxin B_1 can be activated by cytochrome P450, form DNA adducts, and lead to hepatocellular carcinoma. OTA is nephrotoxic and potentially carcinogenic; fumonisins disrupt sphingolipid metabolism with links to esophageal cancer; ZEA perturbs endocrine function and fertility. Analytical surveillance employs chromatographic platforms (LC/GC) with fluorescence, UV, or mass spectrometry, alongside immunoassays and immunoaffinity workflows. Key challenges include achieving trace-level sensitivity, ensuring specificity in complex matrices, and lowering operational costs, which limit monitoring in resource-constrained regions. Regulatory limits, such as those set by the EU, emphasize standardized detection and risk control. Mitigation relies on a farm-to-fork approach integrating good agricultural practices, biological and chemical controls, and effective post-harvest handling. Physical and bioprocessing methods like gamma irradiation, cold plasma, ammoniation, alkaline treatments, and microbial or enzymatic degradation using Lactobacillus, Saccharomyces, laccases, and aflatoxin-oxidase offer practical reduction strategies. Emerging precision biosensors, AI-based risk prediction, and genome-driven biocontrol and enzyme engineering promise earlier detection and improved detoxification. This review synthesizes current insights on toxicology, monitoring, and mitigation to lower human exposure and protect food systems.*

[Citation: Safdar, R., Imran, S., Mushtaq, E., Nasir, A. (2026). From Toxicology to Technology: Human Health Risks of Mycotoxins in the Food Chain and Current Approaches to Their Detection and Control. *Bull. Biol. All. Sci. Res.* **11***: 114. doi:* https://doi.org/10.64013/bbasr.v2026i1.114]
Keywords: *Mycotoxin; toxicological; mutagenic; aflatoxins; ochratoxin; food safety; Fusarium; Aspergillus; Penicillium; detoxification; control strategies*

Introduction

Most filamentous fungi, such as *Aspergillus*, *Fusarium*, and *Penicillium*, develop secondary compounds called mycotoxins, which are harmful to both humans and animals (Magembe, 2025). Fungi have been identified as allergens from an allergy/immunology standpoint that can trigger autoimmune and allergic reactions. Individuals may acquire allergic disorders such as rhinitis, sinusitis, asthma, and hypersensitivity pneumonia depending on their hereditary predisposition (Platts-Mills, 1993). Several *Aspergillus* fungus species, including *Penicillium*, *Fusarium*, and *Trichoderma*, produce health-threatening toxins known as mycotoxins. These toxins are commonly found in food and feed (Tola and Kebede, 2016). These could exist as harmful substances in food and feed such as grains, beans, oil seeds, dairy products, and fruits and vegetables with high moisture and nutritional contents (Gizachew et al., 2016; Marin et al., 2013). Because mycotoxins are extremely poisonous presence of multiple toxins from molds in the same food can change how toxic they are to humans and animals, potentially leading to antagonistic, additive, or synergistic effects. They are one of the biggest issues for public health. Research on mycotoxins has been done all around the world to assess their severity and existence in various food entities (Berthiller et al., 2018; Yu et al., 2004). The presence of different toxins from molds in the same food can change how toxic they are to humans and animals, potentially causing antagonistic, additive, or synergistic effects (Alassane-Kpembi et al., 2017). Acute and chronic toxicities resulting from the consumption of mycotoxins in food can include hepatotoxic,

hemorrhagic, nephrotoxic, estrogenic, neurotoxic, teratogenic, immunosuppressive, mutagenic, and carcinogenic consequences (Ostry et al., 2017). Moisture, severe rains, high temperatures, and unhygienic conditions during haulage and storage are the first factors that promote the creation of mycotoxins (Van Egmond, 2002). Mycotoxins typically result in serious conditions when consumed through unclean food, inhaled spore-borne toxins, or come into contact with mold–infected materials through skin contact (Benkerroum, 2016). The rules were implemented to address mycotoxin-related concerns about food safety. Groundnuts, often known as peanuts, maize, rice, sorghum, wheat, spices, fruit juices, and many more agricultural products are regulated (Bhat and Vasanthi, 2003; Bryden, 2007; Science, 2003). Global trades, human health are all severely affected by mycotoxins. Cereals, nuts, spices, dried coffee, and dairy products are just a few of the agricultural items that could contribute to contamination (Maurya). Decreased production of crops, cattle distortion, higher expenses for inspection of food and manufacturing, and limitations on trades are some of the financial consequences. To safeguard public wellness and promote commerce worldwide. Mycotoxin amount in livestock and food products is regulated and standardized globally (Lee et al., 2021).There are currently more than 500 substances known to be Mycotoxins, but the most Mycotoxins that are often examined and assumed to be the biggest threat to human and animal health are *fumonisins, ochratoxins, trichothecenes, patulin, zearalenone,* and *aflatoxin (*Haque et al., 2020*)*.The mycotoxigenic *Fusarium* fungi that populate the body produce a spacious range of structurally related compounds called *trichothecenes*, which are very important crops in the stages of production before reaping (Ferrigo et al., 2016; Yoshinari et al., 2015).For that reason, it is now challenging to avoid *trichothecene* contamination as a result of the significant outcome of abiotic factors (Ibáñez-Vea et al., 2011). These mycotoxins are members of an enrichment class of cyclic sesquiterpenoids, which includes more than 200 analogs with a range of toxicological effects (Nathanail et al., 2015a; Nathanail et al., 2014).With respect to chemistry, this family of compounds are illustrious by their olifinic bonds with different hydroxyl\acetoxy changes as well as a tetracyclic epoxy C-12 and C-13 organization that is in charge of their toxicity 1(Nathanail et al., 2014; Gab-Allah et al., 2021b)There is customarily partitioned into Types A, B, C, and D, are the four subgroups based on the attributes of substitute groups and the corresponding producers of fungi (Zou et al., 2012).Of the *trichothecenes* that are currently on the market mycotoxins, with type B *trichothecenes* receiving special attention. This primary category of Mycotoxins have been comprehensively dangerous to both agro-food systems and public health because of their extensive geographic distribution (Gab-Allah et al., 2021a). Mycotoxins sturdiness molecules that are likely to remain after processing and are challenging to eliminate in the finished items. There are numerous ways that humans can be exposed to mycotoxins, including ingesting tainted food and drink, breathing in mold spores in the air, and skin contact with surface contaminated by fungi that produce mycotoxin (Ehsanifar et al., 2023; Eivazzadeh-Keihan et al., 2017). Individual may also consume goods from animals that eat mycotoxins contaminated feed (Lach and Kotarska, 2024). Mycotoxin-induced food contamination is a serious problem on a worldwide basis. Regardless Mycotoxin contamination is viewed as an issue in storage, processing, and good agricultural practices fundamental and capricious issue, posing a challenging obstacle to food safety, particularly in developing nations (Alshannaq and Yu, 2017). Apprehension within the European Union (EU) is recovering from the impacts of mycotoxins on the health of people and animals. Along these lines, Commission Regulation (EU) 1881\2006 (No, 1881). and its corresponding amendments set the upper limit of what is allowed for specific mycotoxins, like *aflatoxin B1* (AFB1), found in dried fruits, nuts, and groundnuts, the total of *ochratoxin A* (OTA) and *aflatoxins* B1, B2, G1, and G2 (AFBs).

Mycotoxins are low molecular weight, toxic substances that are produced by fungi that contaminate food and feed. They are tiny, somewhat stable compounds that are difficult to remove from the body (Milani, 2013; Steyn, 1995). Mycotoxins are an assemblage of chemically diverse and toxic substances that are clustered together. There are several mycotoxins whose toxicities to people, animals, and plants overlap (Bennett, 1987). Of all the fungal secondary metabolites, polyketides are most abundant and structurally variable. Acetate and malonate are examples of short-chain carboxylic acid units that are polymerized to create their carbon scaffolds, which have a similar metabolic origin. According to the catalytic domains and enzymatic processes involved in their creation, polyketides, which are biosynthesized by large multipurpose enzymes known as polyketide synthases (PKSs), can be divided into four primary categories (Shen, 2003). It was determined that the biosynthesis of (R)-mellein was highly parallel to that of 6-MSA, necessitating an extra chain expansion and keto reduction. The manufacturing of other dihydroisocoumarins and perhaps the mycotoxin *ochratoxin* are carried out by these PR-PKS genes (Sun et al., 2012). Specific analytical methods, like thin-layer chromatography TLC (Trucksess et al., 1984; Stroka et al., 2000). High-performance liquid chromatography (HPLC) (Manetta et al., 2005; Giray et al., 2007). Thin-layer chromatography in two dimensions (Van Egmond et al., 1991), and ELISA, or enzyme-linked immunosorbent assay (Saha et al., 2007; Reddy et al., 2001), have been attainable for both quantitative and qualitative AF analysis. Alas, the use of TLC is

restricted by separation, poor sensitivity, and unsatisfactory accuracy. ELISA is a quick and accurate technique, but false A favorable outcome could be achieved. The most popular approach, Liquid chromatography coupled with fluorescence detection, is used for AFs analysis, and it has been thoroughly researched in several matrices of food (Manetta et al., 2005;Mortimer et al., 1987; Stubblefield, 1987).

This review will first discuss the chemical nature and occurrence of common mycotoxins, followed by a detailed examination of their toxicological effects on human and animal health. Subsequently, current analytical methods for their determination will be explored, and finally, a comprehensive overview of pre-harvest and post-harvest strategies for mycotoxin control and detoxification will be presented.

Occurrence and sources of mycotoxins

Mycotoxins can be found in an extensive variety of grains, nuts, fruit, juices, and associated items, attracting international interest (Eskola et al., 2020). Each year, so many types of other types of fungal toxins have been noticed, the most prominent are *aflatoxins*, *trichothecenes*, *zearalenone* (ZEN), *fumonisins*, *ochratoxin*, and *penicillin* (Eskola et al., 2020). *Trichothecenes*, *ZEN*, *fumonisins*, *fusarin* C, *moniliformin*, *enniatins*, *beauvericin*, and *fusaproliferin* are among the at least eight types of mycotoxins having toxicological relevance that have been identified to be produced by members of the *Fusarium* genus, a broad group of toxigenic fungi. *Aflatoxin* B1, B2, G1, and G2 are the four primary compounds produced by toxic fungi in the *Aspergillus flavus* section. When consumed by mammals, these compounds can all be produced further variants (Caceres et al., 2020; Navale et al., 2021). Contamination with mycotoxin is thought to be the source of major financial losses, as well as problems with food hygiene and public health, this cannot be fully calculated (Oguz, 2017; Darwish et al., 2016).

The primary food/feed and economic cereal crop in sub-Saharan Africa, particularly in East Africa, is maize, also known as corn (*Zea mays* L) (Kornher, 2018; Santpoort, 2020). Corn/ Maize is mainly grown in tropical and warm temperate regions. Its dietary value is high in comparison to other food and agricultural products (Kornher, 2018). Each portion of the maize plant, the cob, stalk, and the tassels, has a distinct use in the East African Community. To feed dairy animals is the primary purpose of the maize stalk after harvesting. Corn stalk shreds can also be used as organic material in decomposition. The maize plant has several functions, and the same is true for the tassels, which are known to contain essential substances such as phytochemicals, pharmaceutical substrates, and antioxidants (Kortei et al., 2021). As the most essential component of the maize plant, the kernels are found connected to the cob and are eaten in a variety of ways. You can eat maize kernels entirely, ground into four pieces, or roasted or boiled right from the cob. Corn's significance extended across the agriculture and livestock areas to the nutraceutical industry. In the latter case, it has been demonstrated that maize possesses antioxidant qualities since the crop contains phenolic and anthocyanin chemicals (Jacinto et al., 2018). Many variables have consistently challenged maize production, and one of the most common issues is mycotoxins (Mutegi et al., 2018; Kortei et al., 2021; Meijer et al., 2021). The most extensively researched class of mycotoxins is probably *Aflatoxins* (Benkerroum, 2020). According to the first discovery and occurrence, the "Turkey X disease" killed approximately one million turkeys in England in the 1960s (Kensler and Eaton, 2024), as well as twenty thousand ducklings and various partridge poult (GN, 2011; Hell and Mutegi, 2011).

Co-occurrence of mycotoxins

Several samples of foods have demonstrated this phenomenon, which involves the presence of many mycotoxins inside the same matrix. A food product is typically more subject to several mycotoxins as opposed to just one; as a result, it is anticipated that the various mycotoxins will have a combined effect (Mahdjoubi et al., 2020). Because of the paucity of knowledge on potential impacts, the real health concerns have not yet been investigated (Mahdjoubi et al., 2020; Wan et al., 2013). The most prevalent occurrence of dual mycotoxin contamination in a single sample is the co-presence of AFB1 and AFB2. The highly impacted sample of multi-mycotoxins, primarily by AFB1 and total *Aflatoxins* (AFB1, AFB2, and AFG2) as well as other fungi, was found to be peanut paste in recent investigations (Manizan et al., 2018). DON, FUM, and ZEA are the most common mycotoxins worldwide, according to the most current survey conducted by BIOMIN Company. Among the 6844 agricultural product samples examined, their respective prevalence were 66%, 56%, and 53% (Gonçalves and Santos, 2017). Over 60% of the data (Figure 1a), were originated from Europe, whereas just 7% are from North America, and only one study examined samples from Oceania. Raw and refined cereals are the most commonly researched commodity kinds, accounting for 80% of the total data. Milk and its derivatives were the subject of only a few studies, and the majority of the remaining data relates to plant items, notably spices, fruits and nuts (Figure 1b). Overall, Europe comprises around half of the data on cereal-based items (Abbas et al., 1988; Abramson et al., 1997; Abramson et al., 1987; Ali et al., 1998).

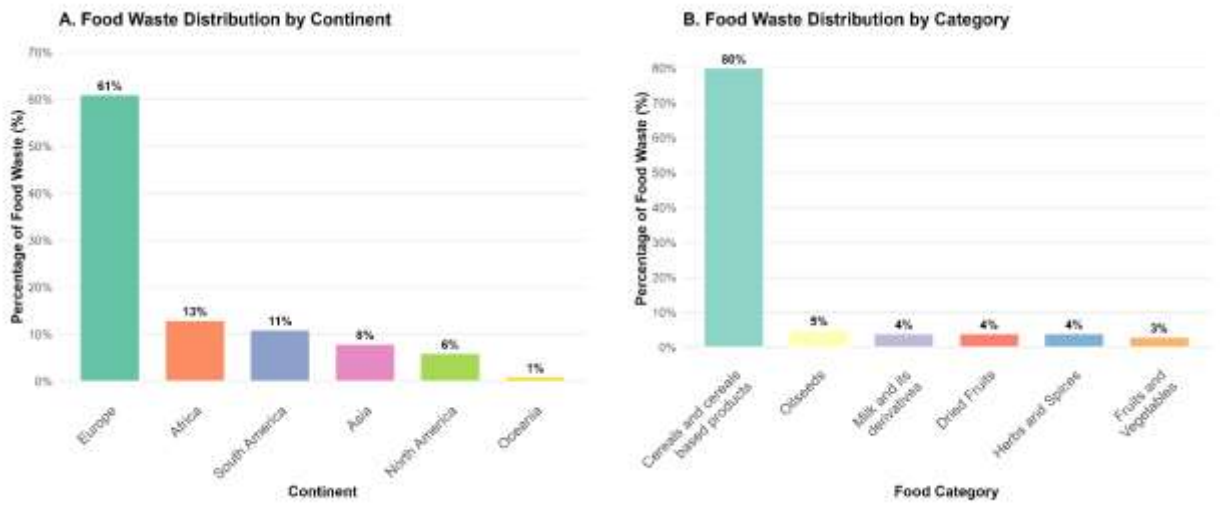

Figure 1: Distribution of data based on (a) geographic regions and (b) commodities information gathered from 107 publications

Types of Mycotoxins

Aflatoxin

Aflatoxins (AFTs) are a group of toxic secondary metabolites produced by filamentous fungi, primarily *Aspergillus flavus*, *A. parasiticus*, *A. nomius*, and *Emericella nidulans* (Ali et al., 2005). These toxins contaminate various food and feed products, as well as raw ingredients used in their processing, posing a serious threat to human and animal health (Wen et al., 2014). The major aflatoxins include *aflatoxin* B1 (AFB1), B2 (AFB2), G1 (AFG1), and G2 (AFG2), along with their hydroxylated derivatives—*aflatoxin* M1 (AFM1) and M2 (AFM2)—which are metabolites of AFB1 and AFB2. Structurally, they belong to the difuranocoumarin family of compounds (Bilotti et al., 2000). They have been linked to metabolic disorders such as aflatoxicosis in both humans and livestock. Among them, AFB1 is considered the most toxic, up to 1,000 times more potent as a liver carcinogen than benzo (α) pyrene (Quality et al., 2007). Due to their severe health implications, especially in relation to increasing cancer incidence, controlling *aflatoxin* contamination is critical. This chapter highlights the sources of contamination, associated health risks, and various strategies for mitigation to ensure food safety (Makun et al., 2011).

Many kinds of *Aspergillus* fungus, particularly the strains *A. favus*, *A parasiticus*, and *A. nomius*, are the main producers of *Aflatoxins* (Aspergillus favus toxins), which are naturally occurring, strong, and carcinogenic compounds. *A. bombycis*, *A. minisclerotigenes*, *A. parvisclerotigenus*, *A. ochraceoroceus*, and *A. pseudotamarri* are additional *Aspergillus* species that generate *Aflatoxin* but to a lesser degree (Probst et al., 2012; Okoth et al., 2018; Frisvad et al., 2019). There are the highly poisonous secondary metabolites of *Aspergillus molds*, including *Aspergillus nomius*, *Aspergillus favas*, and *Aspergillus parasiticus* (Alcaide-Molina et al., 2009; Ali et al., 2005), which the World Health Organization has identified as carcinogenic and genotoxic (Quality et al., 2007). Even at very low concentrations, *aflatoxins* have teratogenic, mutagenic, hepatotoxic, and carcinogenic impacts on human health when consumed, breathed, or absorbed through the skin (Zain, 2011; Wen et al., 2014; Ali et al., 2005). In 1960, it was demonstrated that they were a source of Turkey X illness or liver necrosis (Alcaide-Molina et al., 2009). In Kenya (Africa), *aflatoxins* were also the source of *aflatoxicosis* outbreaks that happened in 1981, 2001, 2004, and 2005 (Makun et al., 2011). The strongest mycotoxin, AFB1, is also known to be hepatotoxic and hepatocarcinogenic. In Kenyan province's eastern region, *aflatoxins* claimed the lives of 123 individuals in 2004 (Nyaga, 2010). Combining a low protein diet with AFB1 exposure, as mentioned in (Rotimi et al., 2018), reduced the rats' onset of renal impairment and weight gain. High temperatures and humidity are ideal for the development of molds and manufacture of toxins, and these conditions are known to favor the growth of *aflatoxin* (Ventura et al., 2004; Zöllner and Mayer-Helm, 2006; Afsah-Hejri et al., 2013). When the pigs were exposed to *aflatoxins* displayed signs of thymic depression along with a reduction in cellular immunity and T-cell activity (Bilotti et al., 2000) (Figure 2).

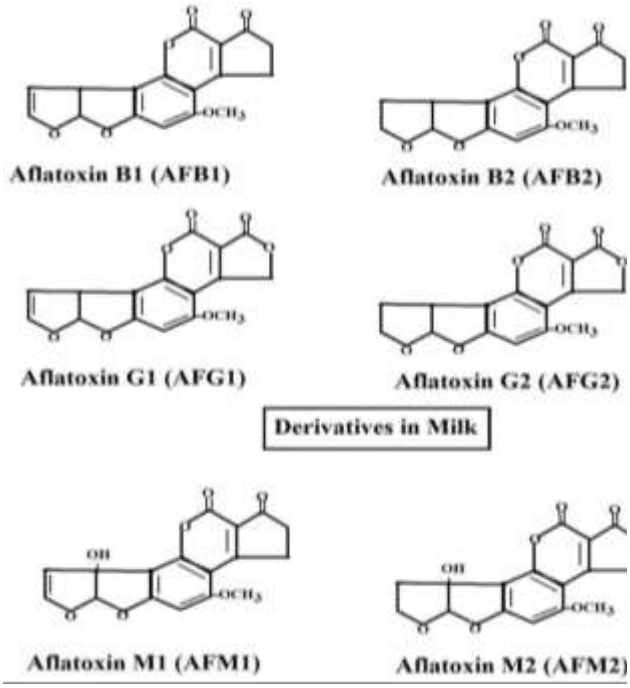

Figure 2: *Aflatoxins* are toxic secondary metabolites from *Aspergillus* species that contaminate food and feed, posing serious health risks, including liver cancer and metabolic disorders (Enespa and Chandra).

Ochratoxin A

Ochratoxin A (OTA), one of the most significant mycotoxins, was initially identified in 1965 (Heussner and Bingle, 2015). This is mostly generated by *Penicillium verrucosum*, *Aspergillus ochraceus*, *Aspergillus carbonarius*, and *Aspergillus nigar* (Ostry et al., 2013; Barrea et al., 2018). A Pentaketide molecule called OTA is generated by coupling a dihydrocoumarin family derivative to β-phenylalanine (Zhu et al., 2017). OTA may cause cancer in humans according to the IARCs classification of it as a group 2B carcinogen. Furthermore, OTA has been described as teratogenic, neurotoxic, immunotoxic, genotoxic, hepatotoxic, nephrotoxic, and embryotoxic (Pfohl-Leszkowicz and Manderville, 2007; Barrea et al., 2018). Various animal species are already known to be carcinogenic, and their signs of OTA poisoning are dependent on dosage. Also, prior research has shown that OTA can cause kidney damage, cancer, or kidney failure in humans; human aspects of OTA poisoning are still not fully known (Heussner and Bingle, 2015). The amount of food consumed is the most common method of OTA exposure (Reddy and Bhoola, 2010). In the human body, more than 20 OTA derivatives are produced both naturally and via biotransformation. Most importantly, OTA uses benzoquinone and intermediaries to create covalent DNA adducts. Additionally, the quinone electrophile quinone (OTQ), which likewise interacts with DNA, can be produced by an autoxidative mechanism from the OTA hydroquinone (OTHQ) metabolites. Its cytotoxicity is also caused by increased creation of reactive oxygen compounds ROS that can arise from the formation of OTQ or phenoxy and aryl redicals. Corresponding to exposure to pentachlorophenol derivatives the mechanism causing OTA nephrotoxicity , hepatotoxicity, immunotoxicity can be connected to the suppression of protein synthesis, lipid peroxidation and the modulation of the MAP kinase cascade (Heussner and Bingle, 2015; Malir et al., 2016; Zhu et al., 2017) (Figure 3).

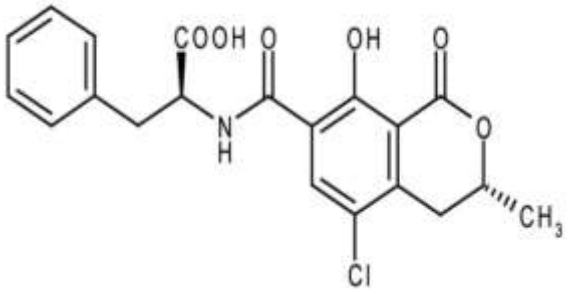

Figure 3: Chemical structure of *Ochratoxin A*, a mycotoxin produced by *Aspergillus* and *Penicillium* species, known for its nephrotoxic, carcinogenic, and immunosuppressive effects.

Fumonisins

Numerous *Fusarium* species, including *Fusarium verticillioides* and *Fusarium proliferatum*, are responsible for producing these (Marasas, 2001). A significant and economically significant species, *F. verticillioides* grows as a corn endophyte in both vegetative and reproductive tissues, frequently without the plant exhibiting indications of illness. It is found in almost all samples of corn. Samples of corn and maize from South Africa and Nigeria have been reported to have it (Egbuta et al., 2015; Ncube et al., 2011). Yet, they can also result in ear rot, stalk rot, and seedling blight, depending on the climate, insect damage, and fungal and plant genotypes (Czembor et al., 2010). There is evidence connecting *fumonisin* to esophageal cancer in humans (Shephard, 2011). Even though it affects animals differently, it has been linked to several diseases, including leukoencephalomalacia in rabbits and horses (Egbuta et al., 2015; Giannitti et al., 2011). *Fumonisin* B1 is a long-chain aminopolyol with multiple hydroxyl and carboxyl groups that structurally mimic sphingoid bases, which allows it to inhibit ceramide synthase. *Fumonisins* are polar substances that dissolve easily in water, acetonitrile, and methanol aqueous solutions (Waśkiewicz et al., 2012; Dall'Asta et al., 2008). *Fumonisin* are chemically composed of a 20-carbon amino polyhydroxy-alkyl chain that has been diesterified with propane-1,2,3-tricarboxylic acid (TCA). The toxicity of *fumonisins* is thought to be caused by their structural resemblance to sphingoid bases and their inhibition of ceramide synthases (CerS), which causes sphinganine to accumulate. This chemical structure is similar to that of sphingosine (So) and sphinganine

(Sa) (Guerre et al., 2022; Riley and Merrill, 2019) (Figure 4).

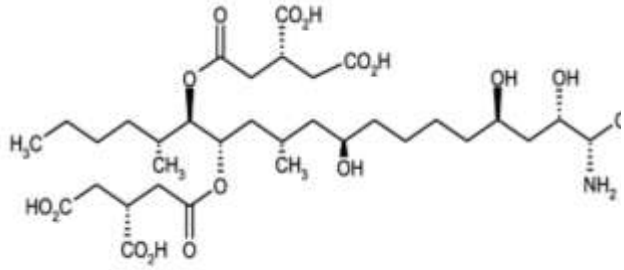

Figure 4: Chemical structure of *Fumonisin B1*, a mycotoxin produced mainly by *Fusarium* species, associated with neurotoxicity, hepatotoxicity, and esophageal cancer in humans and animals.

Zearalenon

It is generally generated from *Fusarium graminearum* and *F. culmorum* fungus species in diverse cereals, including wheat, maize, oat, rye, and barley. It has been shown to cause vulva, edema, breast enlargement, and infertility in a variety of female animals (Zinedine et al., 2007). Accumulation of *Zearalenon* in cereals can be attributed to various factors, including temperature, substrate, fungal strain, and the length of time *Fusariums* grow. It could contaminate food stock as well as food (De Saeger et al., 2003). It has been demonstrated that *Zearalenon* ingestion in tiny doses can hurt animal health, offering major risks and leading to diseases such as pig hyperestrogenic syndrome. Large concentrations of *Zearalenon* can interfere with fertilization, result in abortion, and cause other issues (De Saeger et al., 2003). The aromatic ring on the left side of the *Zearalenone* structure contains hydroxyl groups and contributes to biological activity. The lactone ring in the center is a key structural feature for estrogenic effects. The hydrophobic side chain extends to the right, ending with a ketone, aiding in membrane permeability (Xie, 2005) (Figure 5).

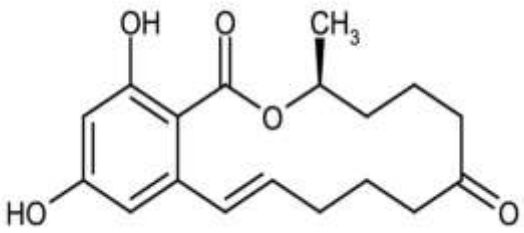

Figure 5: Chemical structure of *Zearalenone*, a non-steroidal estrogenic mycotoxin produced by *Fusarium* species, known to disrupt endocrine function and reproductive health in humans and animals.

Trichothecene

Worldwide in distribution, *Fusarium* species typically generate *trichothecene* in harsh conditions (Nelson et al., 1994). *Trichothecenes* are divided into two groups: those that are non-macrocyclic and those that are macrocyclic. Non- macrocyclic *trichothecene* chemicals are divided into two categories: type A and type B. NEO (neosolaniol), HT-2 toxin, T-2 toxin, and DAS (diacetoxyscirpenol) are among the substances in type A. DON (deoxynivalenol), NIV (nivalenol), 3-AcDON (3- acetyldeoxynivalenol), and 15- AcDON (15- acetyldeoxynivalenol) are examples of class *B trichothecenes* (Hedayati et al., 2007). Trichothecenes are known to induce immune system depression, vomiting, blood and reproductive disorders, growth retardation, dermatitis, and oral lesions (Rocha et al., 2005; Science, 2003). According to Ramirez, the ideal temperature range for *trichothecene* growth is 26-30°C and 0.995 aw water activity (Ramirez et al., 2006). Deoxynivalenol (also known as vomitoxin), nivalenol (NIV), and 15-acetyldeoxynivalenol (15-ADON) are the main types of type B *trichothecenes*, as well as *fusarenon*-X (FUS-X; 4-acetylnivalenol) (Gab-Allah et al., 2021a; Zhao et al., 2014). Mycotoxins have a keto (carbonyl) function and a similar non-,acrocyclic structure. C-8. The fungi species *F. graminearum* typically produce them, which frequently contaminate a variety of cereal grains, such as oats, corn, wheat, rice, and barley (Gab-Allah et al., 2021a; Zhao et al., 2014) (Figure 6).

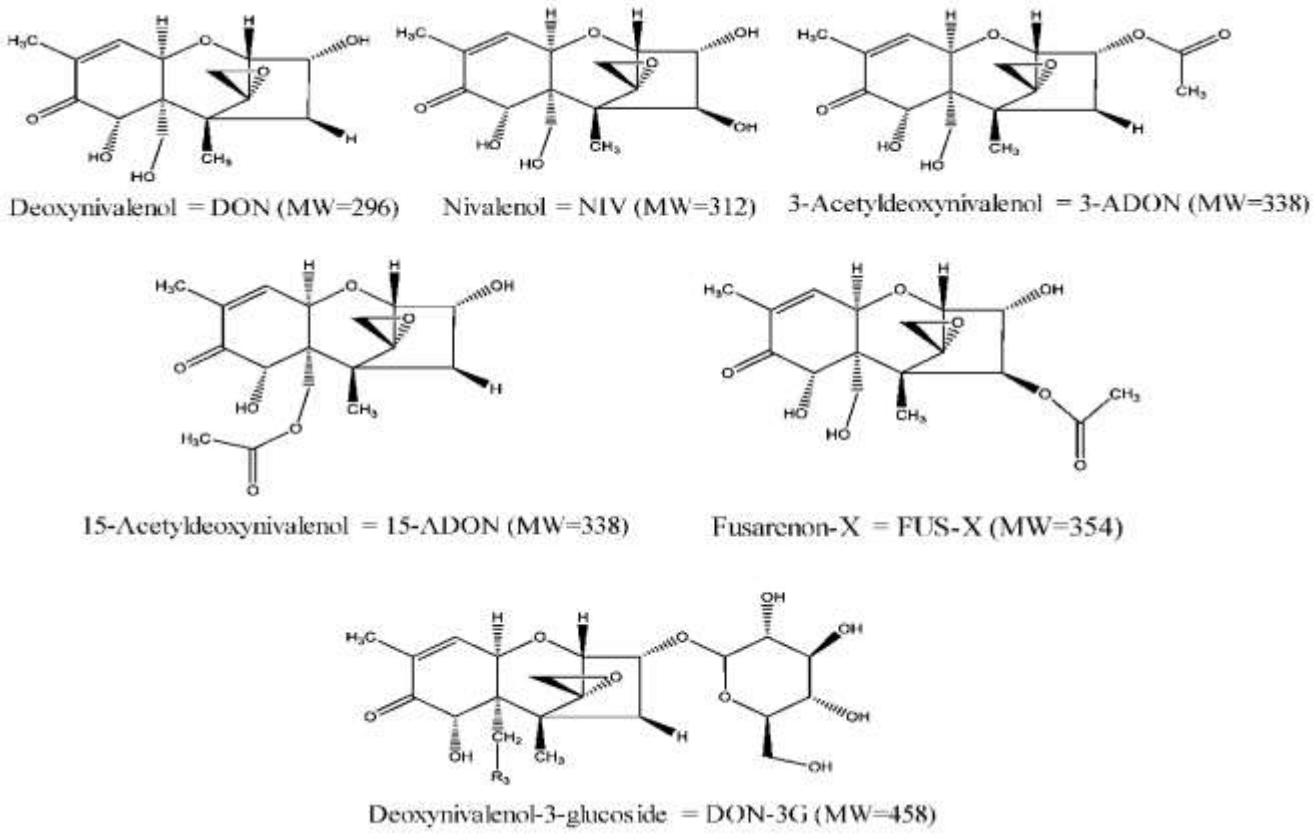

Figure 6: Chemical structures, names, acronyms, and molecular weights of major type B *trichothecenes*, including DON, NIV, 3-ADON, 15-ADON, and FUS-X—and the masked mycotoxin deoxynivalenol-3-glucoside (DON-3G) (Gab-Allah et al., 2023).

Patulin

Patuline is also a poisonous type of mycotoxin generated by different fungus species like *Penicillium patulum*, now termed *Penicillium griseofulvin*. Its chemical formula is 4-hydroxy-4H-furo [3, 2-c] pyran 2 (6H)-one. Patuline has no medicinal use as an antibiotic because it is toxic to both plants and mammals (Bennett and Klich). According to several studies, papain is stable in dry cereals, apple and grape juices, and cereals. However, it may break down in wet cereals (Moss and Long, 2002; Trucksess and Tang, 2001; Armentia et al., 2000). In the laboratory, *patulin* is used as a potassium uptake inhibitor and also induces erythrocyte death at physiological concentrations (Llewellyn et al., 1998). It was formerly used as an antibiotic against both gram-positive and gram-negative bacteria, but its use as an antibiotic has been discouraged due to its toxicity (Lupescu et al., 2013) (Figure 7).

Figure 7: Mycotoxins in food are produced by molds (A) *Aflatoxin*-releasing *Aspergilus fumigatus*; (B) molds on red corn; (C) molds on maize flour; (D) molds on red corn; (E) molds on soybean flour (F) molds on rice grains; and (G)molds on white maize grains; and (H) molds on white corn. Alice N. Mafe took all of the photos (Mafe and Büsselberg, 2024).

Impacts on human and animal health

Mycotoxin entry into the food chain can be made easier by the fungus invasion of crops. Man may consume this directly or through animal feed. About 200 people were treated, and 125 people died in Kenya in 2004 as a result of eating maize contaminated with *aflatoxins*. (Agriopoulou et al., 2020; Lewis et al., 2005; Muñoz et al., 2021). It has been demonstrated that many mycotoxins are harmful in multiple ways. Because molds may easily colonize, they generate toxic biochemical compounds that can cause a variety of deadly diseases in both human and animal habitats (Turner et al., 2009; Bulgaru et al., 2021). Various mycotoxins are included in *Fusarium toxins*, including *fumonisins*, which affect horses, the central nervous system, and may cause cancer in rodents; *zearalenone*, which has not been linked to any fatalities in humans and animals. There have also been reports of central nervous system anomalies (particularly in ducks and turkeys), hepatomegaly, liver damage, and pale livers (Kilic et al., 2022; Wang et al., 2023b; Ghaemmaghami et al., 2024). There have also been reports of immunosuppression, clotting problems, changes in vitamin B and amino acids metabolism, and symptoms including leg weakness and loosened wings in broiler chickens (Wang et al., 2023b) (Figure 8).

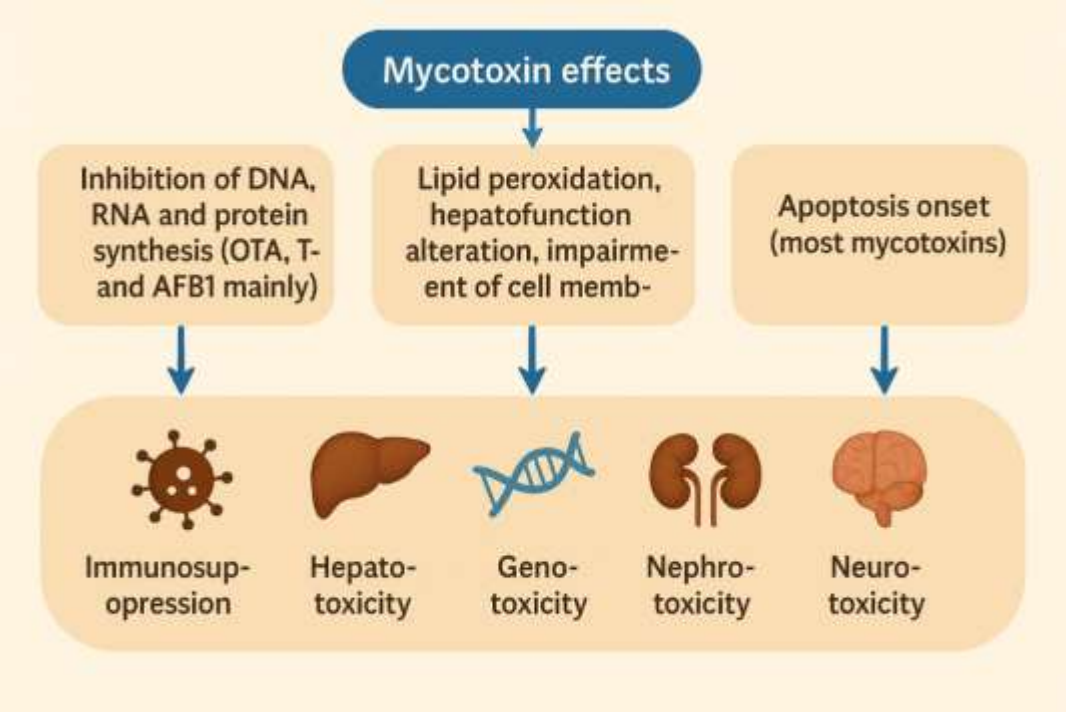

Figure 8: principal processes of mycotoxin poisoning and their repercussions. Mycotoxins can impact several organs and tissues in birds by various ways, including lipid peroxidation, apoptotic regulation, hepatic function impairment, and suppression of protein synthesis. AFB1, *aflatoxin* B1, OTA, *ochratoxin*, RNA< ribonucleic acid, and DNA deoxyribonucleic acid (*Gómez-Osorio et al., 2024*).

Butenolide, enniatins, equisetin, and beauvercin are other (Desjardins and Proctor, 2007). According to the *Assessment of Carcinogenic Hazards to Humans* (2012) and FAO/WHO (2015), aflatoxins are considered among the most harmful and concerning mycotoxins. In Africa, *aflatoxins* are the most prevalent mycotoxin (43.75%), followed by *fumonisin* (21.87%), *ochratoxin* (12.5%), *zearalenone* (9.38%), *deoxynevalenol* (6.25%), and then *beauvericin* (6.25%), according to *Darwish* (Darwish et al., 2014). As a cancer–causing agent (Group 1 carcinogen), *aflatoxin* B1 (AFB1) has been connected to the development of primary liver cancer in humans, where it works in concert with HBV infection. The liver is the primary organ affected by AFB1; however, it can also interfere with other physiological functions. The key issues, meanwhile, continue to be liver toxicity and how it's revolved around products interact with the DNA of liver cells. After prolonged contact with low AFB1 levels, this relationship is associated with the formation of liver tumors. Furthermore, hepato cytochrome P450 (CYP450) enzymes typically activate *aflatoxin* B1, the most common and physiologically active AF, to the cancerous and aggressive AFB1-8-9-epoxide AFBO precursor (Kemboi, 2023). This substance can attach itself to liver cells' DNA to generate an unstable AFB-N7-guanine adduct, which, when found in urine, may serve as an indicator of contamination by AFB1 (Lauwers et al., 2019) (Table 1).

Table 1: Regulatory limits, health risk thresholds, and common food sources of major mycotoxins as defined by the European Union (EU). These values highlight the toxicological concern and prevalence of specific

mycotoxins such as *aflatoxins, zearalenone, fumonisins, ochratoxin A, deoxynivalenol (DON), patulin,* and T-2 toxin in various food and feed products

Mycotoxin	Regulatory Limit (EU)	Health Risk Threshold	Common Food Sources	Reference
Aflatoxins	Up to 4 µg/kg	≥ 2 µg/kg	Nuts, maize, rice, dried fruits, spices	(Peers and Linsell, 1973)
Zearalenone	Up to 100 µg/kg	≥ 50 µg/kg	Cereals, grains, maize, animal feed	(Alemu et al., 2024)
Patulin	Up to 50 µg/kg	≥ 25 µg/kg	Apples, apple juice, fruit-based products	(Piemontese, 2005)
Fumonisins	Up to 4000 µg/kg	≥ 2000 µg/kg	Corn, maize, and maize flour	(Velasco et al., 2023)
Ochratoxin A	Up to 3 µg/kg	≥ 1 µg/kg	Coffee, dried fruit, cereals, wine, legumes	(Wang et al., 2023a)
Deoxynivalenol (DON)	Up to 1750 µg/kg	≥ 1000 µg/kg	Wheat, barley, oats, animal feed	(Obradović et al., 2022)
T-2 Toxin	Up to 1000 µg/kg	≥ 500 µg/kg	Wheat, oats, barley, and animal feed	(Jin et al., 2022)

Certain cancer types are directly linked to certain mycotoxins

Breast cancer

According to a study conducted in North Africa, Apha-zearalanol is likely involved in the progression of blood cancer (Belhassen et al., 2015). Whereas alpha *zearalanol* can come from food consumption or the metabolism of ZEA, it is not yet a fully understood carrier because it can also be found in meat when it is given to cattle to aid in growth (Stephany, 2010). Because ZEA possesses structural similarities with the hormone estradiol, it has an affinity for estrogen receptors and may have an impact on human and cattle fertility. *Zearalenol* and its metabolic products have been shown to have a variety of possible estrogenic actions in vivo. ZEA molar efficacy factors (also known as relative efficacy calculated and applied to estimation factor, or RPFs) have been determined and utilized for estimations for exposure to different ZEA metabolites to account for these variations. By the EFSACONTAM Panel's endorsement, RPFs were molecularly delivered for ZEA and its metabolic products with a-zearalanol RPF 4.0 (Chain et al., 2018). All of these finding indicates that ZEA and its metabolic byproducts may be important contributors to both human and animal reproductive organ cancer (Ahmed Adam et al., 2017; Pillay et al., 2002).

Liver cancer

The relationship between *aflatoxins* and a higher risk of liver cancer has been established by numerous investigations. A higher probability of liver cancer has also been associated with eating foods contaminated with *aflatoxin* (Forner et al., 2015). Cytochrome P450 (CYP 450) oxidizes *aflatoxin* B1 to *aflatoxin* 8, 9-epoxide, a highly reactive and fragile form that can attach to DNA or proteins like albumin (Ahmed Adam et al., 2017; Bbosa et al., 2013; Awuchi et al., 2022). When *aflatoxin*-8, 9-epoxide interacts with DNA molecules, the *aflatoxin*-N7-guanine adduct is created, resulting in G: C to T: A. When DNA is replicated, a transversion mutation occurs (Huang et al., 2017; Wojtacha et al., 2021). Due to the consumption of agricultural foods mostly generated through subsistence farming, *aflatoxins* are associated with the occurrence of HCC in low- and middle-income countries (Turner et al., 2002; Wild et al., 2015). *Aflatoxin* and liver cancer have primarily been researched in relation to HCC, vague PLC, which may account for the inconsistent findings from diverse studies (Forner et al., 2015). Obesity (or being overweight), alcohol usage, liver cirrhosis, long-term use of contraceptives taken orally with strong estrogens, eating foods tainted with *aflatoxins*, smoking, and chronic hepatitis B\C are all factors that affect the possibility of liver cancer. Exposure to *aflatoxin* and HBV infection can have synergistic effects that can be explained by an increase in CYP450 caused by the virus, which transforms *aflatoxin* into its reactive metabolic components (Forner et al., 2015).

Mycotoxin Determination

An analysis of mycotoxin levels provides insight into how pathogenic fungi might infect food and feed. Since 1970, several chemical and biological methods for detection and quantification have been established. Numerous agencies, including the EPA, FDA, and AOAC, have standardized the mycotoxin analysis procedure. Even the detection of low levels of mycotoxins in food and feed commodities can now be done methodically. To analyze Mycotoxin, a proper sampling process that complies with Codex Alimentarius is a crucial step. Food and feed samples do not have the same number of mycotoxins. For accurate analytical results, sample extraction and preparation are essential steps. Three primary steps comprise the examination of mycotoxin: extraction,

purification, and assessment (Lauwers et al., 2019). There are many analytical challenges, including a broad spectrum of mycotoxin chemical structures, the co-occurrence of mycotoxins, challenges in identifying low-level mycotoxin contaminants, complicated matrices where the mycotoxin contaminants occur, and challenging extraction methods (Shephard, 2016).

Method of Extraction

- Solid-phase extraction (SPE), mainly with C18 or immunoaffinity columns (IACs), which contain antibodies that are specific to the analytical substance of interest, is the most frequently used technique for mycotoxin extraction. SLE is the most popular technique for mycotoxin extraction, and is followed by a purification or cleanup step when required (Pereira et al., 2014; Cigić and Prosen, 2009). There is a need for multiclass extraction techniques that are simpler to operate and ecologically friendly. Despite the different methods available, the extraction of a variety of mycotoxins in various food matrices is frequently accomplished using (dSPE) employed for sample preparation (Arroyo-Manzanares et al., 2014).
- Extraction based on partitioning by salting-out, which entails the balance between an aqueous and an organic layer, and
- dSPE extraction for further cleanup using a combination of MgSO4 and other sorbents, including C18 or primary and secondary amine (PSA), is its two-stage process (Arroyo-Manzanares et al., 2014; Iqbal, 2021).

In contrast, a chemical or a collection of compounds that make up a solid is dissolved in a solvent with the proper polarity in a typical SLE. Analogously, polar solvents such as acetonitrile (MeCN), acetone, or methanol (MeOH) can be used to successfully extract the majority of the mycotoxins in this scenario (Bian et al., 2023).To increase the extraction's effectiveness, it is also feasible to wet the material with a little amount of acidified water. This increases the latter's surface area in contact with the solvent and raises the pH, which increases the solubility of mycotoxins (Rahmani et al., 2009). Because this type of extraction is not highly specific, it is usually followed by purification or cleanup to remove any contaminants, including lipids, proteins, and coloring compounds that could interfere with the results of the study. They can be removed in considerable amounts using chelating compounds (C18 and PSA) (Cigić and Prosen, 2009; Rahmani et al., 2009).

Determination via Analysis

The most often utilized analytical techniques for determining mycotoxin levels are gas chromatography (GC), liquid chromatography (LC), thin-layer chromatography (TLC), and high-performance liquid chromatography (HPLC) (Zheng et al., 2006). To achieve quantification, LC and GC can be connected to several detectors, including mass spectrometry (MS), fluorescence (FL), or ultraviolet (UV) (Arroyo-Manzanares et al., 2014). At first, UV and FL were frequently utilized to determine mycotoxin levels (Kirinčič et al., 2015; Schollenberger et al., 2005; Sugita-Konishi et al., 2006; Torović, 2018). These methods of detection are predicated on mycotoxin fluorescence and UV absorption properties. When determining which fluorescent chemicals are present in cereal and pseudo-cereal samples, FL is typically utilized because its sensitivity is typically 10-1000 times greater than that of the UV detector. To analyze AFs, OTA, and ZEA in cereal and pseudo-cereal matrices with high precision and good accuracy, FL detection has been applied extensively (Singh and Mehta, 2020; Torović, 2018). The immunological assay for mycotoxin screening, known as ELISA, is another frequently used method for mycotoxin assessment (Sacco et al., 2020; Keriene et al., 2016). This assay does not require prior clean-up processes and offers quick and affordable readings. The direct, indirect, competitive, and sandwich ELISA formats are acknowledged as suitable for mycotoxin screening. A transduction system with the proper molecular recognition components has been incorporated to support field analysis. Accordingly, various analytical techniques have been created for the identification of TCs, FB1, OTA, and AFs in cereals and pseudo-cereals (Singh and Mehta, 2020) (Table 2).

Table 2: Recent immunoassay-based techniques developed for the detection of major mycotoxins in food products. These include ELISA for *aflatoxins* in peanuts, lateral flow immunoassay for *zearalenone* in cereals, immunoaffinity column-based detection of *patulin* in fruit juices, and magnetic nanoparticle-assisted assays for multi-mycotoxin detection in wheat

Technique	Findings
ELISA	Devised a distinctive ELISA technique for extremely sensitive aflatoxin detection in peanuts (Hafez et al., 2021).
Lateral Flow Immunoassay	Established an immunoassay using lateral flow for the quick detection of zearalenone in cereal goods (Wang et al., 2022).
Immunoaffinity Columns	Demonstrated high recovery rates by extracting and detecting patulin in fruit juices using immunoaffinity columns (Sadhasivam et al., 2021).
Magnetic Nanoparticle	Generated magnetic nanoparticles and immunoassays to identify several mycotoxins in wheat (Guo et al., 2023).

Neurological Toxicity

There are very few cross-sectional surveys that document a link between neurological signs and exposure to molds (Baldo et al., 2002). Ergotism, eating tainted food, and possibly other poisonous mushroom poisoning are the main causes of concern. Hallucinations and convulsions are possible side effects of ergot intoxication. When present in sufficient amounts and for long enough periods of time, other fungal constituents such as volatile organic compounds (VOCs) can have neurological effects (Hudnell et al., 1992; Otto et al., 1992; Dalton, 2003). The production of 3-nitropropionic acid by the Arthrinium species has been linked to the symptoms of Kodua, or "Moldy sugar cane poisoning", which includes dystonia, convulsions, carpopedal spasm, and coma (Liu et al., 1992; Ludolph et al., 1991). The production of cylopianzonic acid by both *Penicillium* and *Aspergillus* species has been associated with Kodua poisoning (Rao and Husain, 1985). In clinical terms, these sufferers exhibited shaking hands, excitement, and drowsiness. Vertuculogen and penitrem A (a mixture of *Penicillium* and *Aspergillus* species) are recognized "tremorgenic" mycotoxins that have not been observed in humans but may cause tremors, ataxia, and convulsions in animals (Sobotka et al., 1978). The intraperitoneal injection mode of administration, which has dubious therapeutic relevance in humans, is a significant limitation of this animal investigation (Breton et al., 1998). There has not yet been any report of particular neurological abnormalities following exposure to *trichothecene* and *stachybotrys*. No neurological signs or indicators were observed, even in possible juvenile consumption instances in which toxic molds were discovered (Montana et al., 1997). As of right now, there isn't any convincing proof that exposure to mycotoxin and indoor molds causes brain harm (Lees-Haley, 2004).

Hematological and Immunological Hazards

Without any rigorous research, there are theories suggesting that mold spores have immunosuppressive properties. Pancytopenia following ingestion of grain infected with *trichothecene* is the initial observation that led to concerns regarding the hematologic or immunologic effects of mycotoxins (Drobotko, 1945). While some research on animals indicates that mycotoxins have an impact on the immune system (Giambrone et al., 1978; Corrier, 1991), by inhibiting peptidyl transferase, *trichothecenes* prevent the production of DNA and RNA, which in turn prevents the creation of protein. Actively proliferating cells are damaged first, which is analogous to being exposed to radiation (radiomimetic) (Lafarge-Frayssinet et al., 1981). Research on the immunosuppressive properties of mycotoxins in animals is not indicative of human exposure. It is impossible to apply the results of this animal research to humans because it involved the oral or intraperitoneal injection of purified high-dose poisons. After consuming *trichothecene*, observational studies (Dales et al., 1998) on individuals exposed to *Stachybotrys* have not shown any signs of radiomimetic effects in alimentary toxic *aleukia* (ATA). Research on natural killer (NK) cells, the CD4/CD8 ratio, and other cytometric parameters did not provide statistically or clinically meaningful results (Johanning et al., 1996). Research indicating immunomodulation by mycotoxins did not consider several confounding factors, including nutrition, endotoxins, VOCs, pests, and dust mite antigens. As of right now, no proof that breathing in mycotoxin can significantly decrease or modify immunity (Bondy and Pestka, 2000).

Gastrointestinal Toxicity

When consumed, mold-contaminated food products and perhaps mycotoxins might result in nausea, vomiting, diarrhea, and abdominal pain (Liu et al., 1992; Bhat et al., 1997). The direct harmful effects on GI mucosal surfaces are connected to the toxicity mechanism. Similar harmful consequences are caused by mushroom toxicity (McPartland et al., 1997; Broussard et al., 2001).

Environmental and storage conditions favoring mycotoxin production

Environmental factors can lead to a higher incidence of mycotoxins: specifically, dryness and high temperature impact crops such as maize, and the presence of *A. flavus* promotes fungal development (Leggieri et al., 2021; Ojiambo et al., 2018). Based on accessible information, it is expected that the amount of CO2 will double or triple in the next 25 to 50 years. It is anticipated that drought periods and CO2 concentration will cause temperatures in several European locations to rise by 2 to 5 °C (Leggieri et al., 2021; Gregory et al., 2009; Bebber and Gurr, 2015; Bebber et al., 2014). European Food Safety Authority (EFSA) acknowledged altered patterns in mycotoxin generation as a result of this scenario and has asked for the identification of new hazards (Leggieri et al., 2021). In the past ten years, the link between climate change and food safety has been receiving a lot of attention globally, raising concerns about how climate-related factors like drought stress, high temperatures, and increased levels of CO2 concentration [CO2] interact to affect the pathogenicity of mycotoxigenic fungi and contamination of major food crops with mycotoxin (Medina et al., 2015; Yao et al., 2021) (Figure 9).

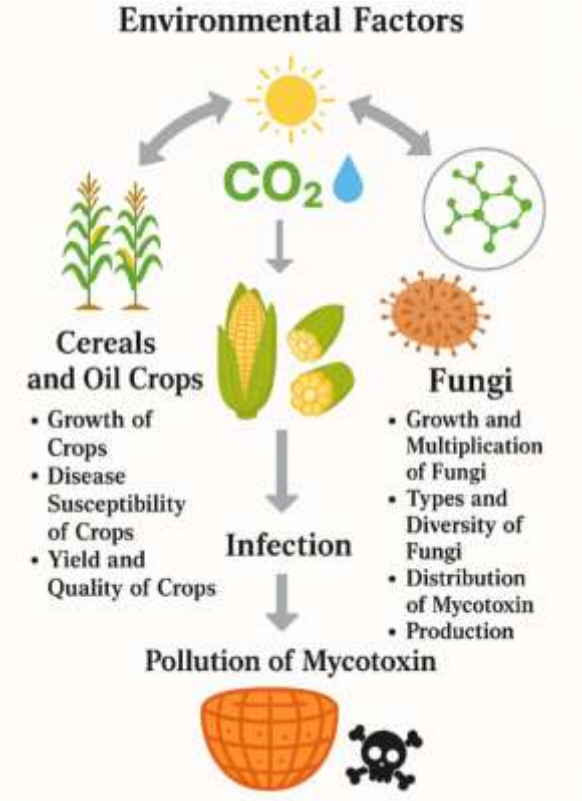

Figure 9: Environmental factors like CO_2, water, and sunlight affect crop and fungal growth. These interactions lead to mycotoxin contamination and crop infection (Zhang et al., 2024).

Strategies for Mycotoxin Prevention and Control

Contamination of mycotoxins is very harmful for both animals and humans, so it is necessary to control mycotoxin contamination in food and feed. There are some methods that are modified to control mycotoxin.

Inactivation/detoxification of mycotoxin

Physical processing

Sorting

Broken and damaged kernels are more likely to contain mycotoxin contamination; uncooked cereal frequently includes dust and admixtures (Juan et al., 2012; Johansson et al., 2006). To eliminate admixtures from grains, sorting, dehulling, or washing is often done either before or after harvesting (Grenier et al., 2014). This process is typically used as a way to keep food quality intact by separating inferior particles from it (Miedaner and Geiger, 2015).

Processing

Dehulling is a fundamental processing step before grains are ground; it involves the removal of the outer layer of the grain. Dehulling has been shown to lower the fungal load from the bulk because fungal colonization builds up on the grain's surface, which lowers the level of mycotoxin contamination (Vučković et al., 2013). According to a study done on maize in Kenya, dehulling the grain when making the traditional dehulled dish muthokoi reduces the number of *aflatoxins*. When compared to whole maize kernels, muthokoi were exposed to a lower level of *aflatoxin* due to a considerable reduction in *aflatoxin* contamination (Kilonzo et al., 2014).

Radiation

Radiation, like gamma rays, UV, sunlight, and microwaves, can partly remove mycotoxins from food by killing harmful bacteria. Because radiations give both food ingredients and contaminant energy, it may be used industrially to remove contamination from food. Extremely high-energy photons produced by gamma radiation directly harm the DNA of cellular microbes (da Silva Aquino, 2012). Several studies have documented the effectiveness of using gamma radiation to reduce *aflatoxin*. AFB1 has been identified to exist 95% less when subjected to a dosage of 10kGy gamma radiation in a study of naturally infected maize (Markov et al., 2015). In a related investigation, red chilies treated to a dose of 6kGy gamma radiation showed an 85% or greater reduction in *aflatoxins* (Iqbal et al., 2013). Even so, only 11-21% of *aflatoxin* reduction at a dosage of 15kGy was recorded in another recent investigation (Di Stefano Vita et al., 2014).

Cold plasma

It is stated that the cold plasma technique is a reliable way to get rid of microorganisms when processing food. The technique's robust antibacterial properties, as emphasized by a recent review, make it suitable for sterilizing surfaces that are susceptible to temperature changes, including food items (Schlüter et al., 2013). Synthetic air is used as the working gas to make the cold plasma which is mostly produced by atmospheric dielectric discharge; in one case study, ZEN and DON concentration were reported to drop from 100 microgram mL 1 to a few micrograms mL-1 (Ten Bosch et al., 2017). Since this technology has not yet been investigated, food products treated with plasma need to be evaluated for the creation of any harmful components during the procedure. There aren't many studies on the use of cold plasma to reduce mycotoxin levels. One study, on nuts, used low-pressure cold to eliminate *aflatoxins* from surfaces by 50% (Basaran et al., 2008). In yet another new study, the ability of palm fruits to produce *Aspergillus* Niger spores was assessed using argon cold plasma at atmospheric pressure. Following treatment for nine minutes, all fungal spores were eliminated, and the concentration of additional mycotoxins likewise decreased below limits of detection (Ouf et al., 2015).

Chemical methods

Numerous substances have been discovered to be helpful for the mycotoxin removal (Carvajal-Moreno, 2015; Chepkirui, 2013); oxidizing agents, chlorinating/reducing agents, salts, different acids, bases, and other substances, like formaldehyde, are among them. Ammoniation is a commonly used technique (Allameh et al., 2011). It has drawn interest for its successful application in detoxifying feed contaminated with *aflatoxin* or *ochratoxin*, and has been utilized in several nations. In corn, wheat, and barley, it entirely breaks down OTA (Nathanail et al.,

2015b). This process results in the observed changes in sensory and nutritional properties, such as brown coloration of the treated cereals and reduction in sulfur- and lysine-containing amino acids, but it does not cause the formation and accumulation of toxic breakdown products of mycotoxins in agricultural products. Amino acids in certain areas of the United States. Ammoniation is a recognized method for cleaning agricultural products and feeds tainted with *aflatoxins*. Furthermore, Ammoniation is employed in Senegal and France to detoxify Mycotoxin-contaminated meals made of maize, cotton, and peanuts (Park and Price, 2001). It has also been discovered that alkaline hydrogen peroxide, sodium hydroxide, monomethylamine, or ammonium with calcium hydroxide treatments are efficient ways to decontaminate this matrix of OTAs (Varga et al., 2010). Plant extracts and essential oil-plant products have recently been used as fungicides to limit the growth of mycotoxin-producing fungi (Choudhary and Kumari, 2010).

Microbiological Methods

Enzymes from microorganisms can be used to detoxify mycotoxins. The microbial ecology of the mammalian gastrointestinal system, particularly the rumen micro-organisms of sheep and cows, has been reported in multiple instances to exhibit OTA degrading activity (Rodrigues, 2014). Furthermore, it has been demonstrated that a wide range of different *bacteria*, *protozoa*, and *fungi* could break down OTA (Chang et al., 2014). It has also determined that lactic acid bacteria, propionic acid bacteria and bacillus species could prevent the growth of fungi and the creation of mycotoxin (Bunaciu et al., 2015), certain enzymes including commercial proteases lipases from *Aspergillus Niger* and *carboxypeptidase* (Abrunhosa et al., 2010).

ZEN degradation caused by microbes

Using microorganisms like *Saccharomyces cerevisiae* and *Bacillus*, which are also involved in feed production, was the most probable way for ZEN decontamination to guarantee feed safety. As a result, we primarily concentrated on the two types of microbes (Zhang et al., 2016) discovered that within 48 hours, *S. cerevisiae* separated from the grape could break down the 2.75 micro g/ml of ZEN concentration in the fermentation broth. Keller and associates (Keller et al., 2015) demonstrated that in two days, the *S. cerevisiae* taken from silage could remove more than 90% of the ZEN from the cultivation medium. Both investigations have demonstrated that *S. cerevisiae* did not merely decontaminate ZEN by adsorption; more research is required to fully understand the degradation mechanism. Lei et al. screened B. subtilis ANSB01G samples from normal broiler intestinal chime (Lei et al., 2014). Because they can be added during food fermentation to break down *aflatoxins* in the production process, lactic acid bacteria that have real-world uses in food production have drawn a lot of interest. *El-Nezami* identified two *Lactobacillus rhamnosus* (GG and LC-705) and *Propionibacterium* (El-Nezami et al., 2000; Gratz et al., 2007). In the Caco-2 model, it showed protection against membrane and DNA damage and was able to extract 54% of AFB1 from chicken intestinal juice medium in just one minute. The binding-degradation of *aflatoxins* was evaluated by *Peltonen et al*. (Peltonen et al., 2001). In light of this, the food and feed industries have benefited from several research and publications on the crucial enzymes for detoxification of *aflatoxins* in recent years (Kolosova and Stroka, 2011). It has been demonstrated that a variety of enzymes, such as laccase (Alberts et al., 2009), aflatoxin-oxidase (AFO) (Cao et al., 2011; Wu et al., 2015), horseradish peroxidase (Das and Mishra, 2000), and others, may breakdown *aflatoxins*.

Comprehensive Mycotoxin Management Strategies

Solutions or techniques to prevent mycotoxin contamination might be either pre- or post-harvest (Awuchi et al., 2021). Harvesting crops on time, minimizing overly wet harvesting conditions, and, if required, curing crops before preservation are all examples of preventive actions throughout the harvesting procedure (Zhang et al., 2018; Kumar and Kalita, 2017). By implementing innovative methods, including air sterilization, overpressure sectors, filtration, and disinfections of atmospheres and surfaces, the agri-food industry today aims to manufacture food under hygienic conditions while maintaining a high standard of quality and safety. These days, avoiding fungal contamination in agriculture is a difficult endeavor; Food can be disinfected utilizing several techniques, such as chemical, biological, and physical procedures. Hardly do they eliminate the mycotoxins, but the majority can degrade or remove them to some extent (Ostry et al., 2013).

Post-harvest control

Preventing alternative mycotoxin contamination in stored crops or vegetables requires post-harvest measures. These approaches include cold storage and other physical and processing techniques meant to lower the levels of Alternaria mycotoxin in food items. It has been discovered that fresh tomato fruits, apples, and lettuce stored at 4 °C produce fewer Alternaria mycotoxin (da Cruz Cabral et al., 2019; Mao et al., 2023; Miranda-Apodaca et al., 2023). Tomato AOH and AME content might be cut in half with a suitable washing method, specifically when using sodium hypochlorite solutions, and heat treatment (110 °C, 30 min) (Meno et al., 2022). Surprisingly, (Bretträger et al., 2023) examined alternative mycotoxin concentrations at different stages of the beer brewing process and demonstrated that optically sorting of malt batches can reduce Alternaria mycotoxin concentrations, especially for AOH and AME. Moreover, as stated by (Pavicich et al., 2020), AOH, AME, TeA, and TEN quantities of Alternaria mycotoxins were reduced to non-

quantifiable levels through clarification during the production of apple concentrates. When compared to untreated fruits, (Jiang et al., 2019) showed reduction of 79.6%, 76.45%, and 51.4% in AOH, AME, and TeA concentrations, correspondingly, demonstrating the effectiveness of using UV-C irradiation in preventing Alternaria mycotoxin formation and infiltration in tomatoes during storage. Moreover, studies using the whole grain red sorghum flour extraction processing method have shown that modulating processing parameters about temperature and moisture content is effective in reducing Alternaria mycotoxin contamination (Janić Hajnal et al., 2024).

Pre-harvest strategy

Good Agricultural Practices (GAPs), which involve the limited use of registered insecticides, fungicides, and herbicides to mitigate the destruction caused by the respective agents, are one type of pre-harvest strategy. A vital element of pre-harvest methods is the proper treatment of the soil bed and soil analysis to confirm the need for compost or to find the genetic synthesis needed to inhibit the generation of mycotoxin (Rai et al., 2018; Muñoz et al., 2021). Furthermore, the use of biological control agents, such as the use of fungi that inhibit fungal growth, is crucial in pre-harvest techniques to prevent mycotoxin contamination in common cereals, grapes, and apples. Good Manufacturing Practices (GAMs) must be adhered to in tandem with Hazard Assessment and Critical Control Points (HACCP) for food processing facilities (Sarrocco et al., 2019). By regulating different environmental conditions like temperature and humidity, which are thought to have the greatest effects on the toxin-producing fungus, mold growth and mycotoxin production can also be decreased. The growth of toxigenic fungi can also be considerably reduced by using good storage techniques, such as controlling the warehouse's temperature, humidity, and moisture content (Hellany et al., 2023). Since the introduction of mycotoxin can be controlled without using any kind of physical and chemical initiatives it is of extreme significance. It can be performed by both sound farming techniques along with resistant seeds with a changed genome (Zadravec et al., 2022) (Figure 10).

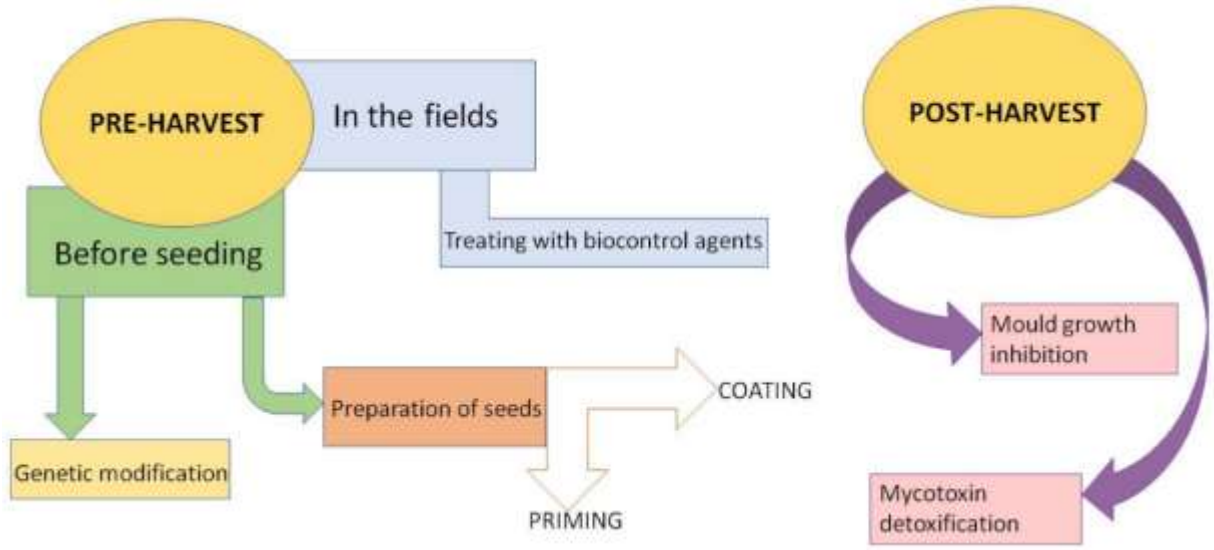

Figure 10: Strategies for grain biocontrol both pre and post growing mycotoxin population (Zadravec et al., 2022).

Future prospects

Novel possibilities as well as challenges and difficulties emerge, mycotoxin management and control continue to change. To properly solve these problems additional investigation and the use of cutting-edge technology are vital. Our capacity to detect, manage, and lessen the hazards related to mycotoxins can be enhanced by discovering research gaps and keeping up with new developments, such as precise biosensors, machine learning models, and genome editing tools. In the face of changing dangers, this proactive strategy insures that food safety methods stay agile and successful (Papatheocharidou and Samanidou, 2023).

Research Deficits

Understanding mycotoxins and their effects on food safety has developed significantly in recent years. The establishment of more productive detection, management and control techniques is impeded by a number of significant research gaps, the needs they fill, and the prospects for further study to enhance food safety and lessen the hazards posed by mycotoxins (Janssen et al., 2019) (Table 3).

Table 3: Key analytical challenges in mycotoxin detection, highlighting issues of sensitivity, specificity, and cost. The table outlines the nature of each issue, the associated technical and practical challenges, and their potential impact on food safety and public health

Issue	Description	Challenges	Impacts

Sensitivity	It can be difficult to accurately detect mycotoxins in food since they tend to exist in extremely low amounts. To ensure accurate safety assessments, analytical techniques must be sensitive enough to detect traces of mycotoxins (Odjo et al., 2022).	Several mycotoxins can be difficult to identify because of their low natural abundance or because matrix effects concealed them. In order to maximize sensitivity and reduce false negatives, analytical techniques must be adjusted (Mafe and Büsselberg, 2024).	Being insensitive may cause contamination levels to be under appreciated, which could result in customers receiving contaminated food products (Mafe and Büsselberg, 2024).
Specificity	Detection techniques' precision is essential for identifying mycotoxins from other substances with equivalent molecular characteristics. False positive or incorrect quantification may result from cross-reactivity with other compounds (Čolović et al., 2019).	Various techniques, such as immunoassays, may not be very specific and may cause cross-reactivity with molecules that share structural similarities. As a result, it's critical to confirm that the techniques are able to precisely target the desired mycotoxin (Mafe and Büsselberg, 2024).	Insufficient specificity may result in inaccurate safety evaluations or needless regulatory actions, as well as impair the precision of results (Mafe and Büsselberg, 2024).
Cost	Due to devices, reagents and upkeep expenses, advanced analytical procedures like high-performance liquid chromatography- mass spectrometry (HPLC-MS) can be costly. This may restrict their limited resources, particularly in environments with restricted resources (Chilaka et al., 2022).	Substantial expenses may limit the quantity of samples examined and the frequency of testing, which could result in tracking lapses and higher risk of mycotoxin contamination going unnoticed (Mafe and Büsselberg, 2024).	Extensive testing programs may be able to deployed due to cost, particularly in poor nations with limited funding (Mafe and Büsselberg, 2024).

Conclusion

Food-borne mycotoxins remain a major public-health concern. Ingestion can cause clear gastrointestinal illness, while current human data do not show major immune harm from indoor mycotoxin inhalation in immunocompetent people beyond allergy and transient irritation. Effective control starts on the farm and continues after harvest through good agricultural and manufacturing practices, careful drying and storage, sorting, washing, heat or UV treatment, and HACCP-based processing. Biological tools and food-compatible microbes such as *Lactobacillus* and *Saccharomyces*, and enzymes like laccase and aflatoxin-oxidase, show promising detoxification potential. Monitoring still struggles with sensitivity and matrix effects at trace levels and needs continued improvement. Climate change is likely to shift fungal ecology and raise contamination pressure, so surveillance must adapt. Looking ahead, precision biosensors, machine-learning risk prediction, and genome-enabled biocontrol can strengthen early warning and mitigation, guided by clearer epidemiology and coordinated policy.

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Statements and Declarations

Data Availability Statement

All data are fully available and can be found within the manuscript file.

Acknowledgement

Not Applicable

Conflicts of Interest

The authors declare no conflict of interest.

Ethics Approval Statement

Not applicable.

Ethics Approval Statement

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Author Contributions

Conceptualization by RS, MI and EM; RS, and SI writing—original draft preparation was prepared by EM, AN, writing—review and editing by AN., and SI; All authors have read and agreed to the published version of the manuscript."

Funding

Not applicable.