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Mycotoxigenic fungi in oilseeds: Occurrence, risk and sustainable management strategies-A comprehensive review

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Abstract

Oilseeds are commercially significant commodities that account for a substantial share of worldwide edible oil production, international trade and food security. Nevertheless, mycotoxigenic fungal contamination is one of the major constraints that impacts oilseed quality, safety and marketability, leading to significant yield and economic losses estimated at 5–25 %. Mycotoxins are toxic secondary metabolites produced by filamentous fungi that infect oilseeds during cultivation, harvesting, processing and storage. Among the most significant fungal contaminants, *Aspergillus, Fusarium, Penicillium* and *Alternaria* are associated primarily with groundnut, sunflower, sesame and *Brassica*, where they produce aflatoxins, ochratoxin A, fumonisins and *Alternaria* toxins. Owing to their hepatotoxic, nephrotoxic, immunosuppressive, mutagenic and carcinogenic properties in human and animal populations, these contaminants pose major health challenges. Advanced analytical techniques such as enzyme-linked immunosorbent assay (ELISA), high-performance liquid chromatography (HPLC) and liquid chromatography-tandem mass spectrometry (LC–MS/MS) facilitate the sensitive detection and quantification of multiple mycotoxins in complex oilseed matrices, enabling precise real-time monitoring. Recently, various management strategies for the prevention and detoxification of mycotoxins via physical methods such as sorting, irradiation and refining, chemical methods involving ozone and organic acids and biological strategies based on microbial and enzymatic degradation have been developed worldwide. This review focuses on climate-resilient management strategies, viz., rapid onsite detection technologies, predictive risk assessment tools and sustainable biological interventions to reduce mycotoxins and ensure a safe oilseed production system.

Keywords: aflatoxin; *Aspergillus*; detoxification; food safety; mycotoxins; oilseed

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1. Introduction

Mycotoxin contamination represents a major global food-safety and food-security concern because toxigenic fungi can contaminate agricultural commodities before harvest and throughout harvesting, processing, transportation and storage. Oilseeds are particularly important because commodities such as groundnut, sunflower, sesame and soybean can serve as substrates for toxigenic fungi, including *Aspergillus*, *Fusarium*, *Penicillium* and *Alternaria*, resulting in contamination by aflatoxins, fumonisins, ochratoxin A and *Alternaria* toxins (1, 2). These contaminants can adversely affect human and animal health and reduce the quality, marketability and economic value of oilseed commodities. The persistence of several mycotoxins through conventional processing further increases the need for effective detection, prevention and sustainable detoxification strategies (3, 4).

"Mycotoxin" is a term coined in 1960 to describe the toxic, low-molecular-weight secondary metabolites produced by filamentous fungi that colonise a variety of agricultural products (e.g., cereals, oilseeds, nuts, dried fruits, spices). Although not necessary for the growth of fungi, these compounds play a key role in ecological fitness and competitive survival. From a food safety perspective, mycotoxins are considered serious worldwide issues because of their persistence, chemical stability and resistance to conventional processing methods. For example, conventional roasting or frying can reduce fumonisins but may not achieve complete detoxification, whereas oil refining can only partially reduce ochratoxin A, with residual toxins potentially remaining in the refined oil or secondary products (3). Fungal growth and subsequent mycotoxin biosynthesis are significantly affected by environmental factors, mainly temperature, water activity (aw), pH and relative humidity. Fungal growth can occur across a broad

temperature range, but the optimum growth and mycotoxin-production conditions vary considerably among fungal species and strains and are also influenced by water activity and other environmental factors (1, 2). Fungal growth is generally favoured by acidic to near-neutral pH conditions, although the optimum pH varies among fungal species and strains and is influenced by temperature and water activity (1, 2). Nevertheless, the water demands generally needed are significantly higher with active mycelial growth (aw ≈ 0.85) and maximal metabolic activity and toxin generation are close to saturation (aw ≈ 0.99). Fungal infection in field environments occurs at relative humidity levels ranging from 70–90 % and at moderate temperatures ranging from 20–25 °C, whereas storage fungi such as *Aspergillus* and *Penicillium* spp. are known to adapt to low moisture and high temperatures (2). This ecological divide between field fungi and storage fungi is key to understanding on contamination dynamics across the production-to-storage continuum.

Mycotoxin contamination is highly geographically heterogeneous worldwide, with moderate to high prevalence reported in Southeast Asia, Oceania and Europe and especially high levels of contamination in North and Central America and South Asia. Among the many mycotoxins that have been identified, aflatoxins (AFB1, AFB2, AFG1, AFG2 and AFM1), ochratoxin A (OTA) and fumonisins (FB1, FB2, FB3) are the most studied, being mostly known for their high toxicity and common prevalence. Trichothecenes such as type A toxins (T-2, HT-2) and type B toxins (deoxynivalenol (DON), zearalenone (ZEN) and others) further contribute to the global mycotoxin load. Other types, including newly discovered and less-regulated toxins such as fusaproliferin, moniliformin, beauvericin, enniatins, NX-2 toxin, ergot alkaloids, *Alternaria*-derived toxins (for example, alternariol, alternariol methyl ether, altenuene and tenuazonic acid) and patulin, among others, have received widespread attention due to their potential adverse health effects (3).

Mycotoxicosis, results from ingestion, inhalation, or dermal contact with substrates contaminated with mycotoxins (4). The toxicological effects of mycotoxins vary depending on the compound, dose and exposure time. The impacts documented in the literature include hepatotoxicity, nephrotoxic, immunosuppressive, endocrine aberrations, teratogenic, mutagenic and carcinogenic effects. Additionally, some mycotoxins disrupt gene expression, protein synthesis and cell communication, causing systemic physiological and reproductive dysfunction, gastrointestinal disturbances and cancer risk factors (5, 6).

Literature search methodology

A comprehensive literature search was conducted to identify relevant scientific publications on mycotoxigenic fungi, mycotoxin occurrence, health risks, detection methods, prevention and detoxification strategies in oilseeds and oilseed-derived products. The literature was searched via electronic databases including Scopus, PubMed and Google Scholar. The search covered publications available from 1969–2025, with an emphasis on recent studies to capture current developments in mycotoxin detection, risk assessment, sustainable management and emerging detoxification technologies. The search was performed via combinations of keywords such as “mycotoxins”, “mycotoxigenic fungi”, “oilseeds”, “aflatoxin”, “Aspergillus”, “Fusarium”, “ochratoxin”, “fumonisins Z”, “mycotoxin detection”, “mycotoxin prevention”, “mycotoxin detoxification”, “biological control”, “nanotechnology” and “oilseed products”. Publications were included when they addressed the occurrence, toxicological significance, detection, regulatory aspects, prevention, or detoxification of mycotoxins associated with oilseeds or oilseed-derived products. Peer-reviewed research articles, review articles and relevant authoritative reports were considered. Duplicate records, studies unrelated to oilseeds or mycotoxins and publications lacking relevant information were excluded. The retrieved literature was critically evaluated and thematically organised according to mycotoxigenic fungi, major mycotoxins, health risks, regulatory and analytical aspects, prevention and detoxification strategies and future sustainable management approaches.

Major mycotoxigenic fungi in oilseeds

Owing to suboptimal storage conditions, oilseed crops are extremely susceptible to progressive diseases that occur after harvesting, which allows colonisation by various seed-borne pathogens. Fungal contamination, which directly impacts seed quality, viability and safety, is a major challenge during storage. The lack of resistance in storage fungi, in contrast to bacterial or viral pathogens, indicates their adaptability to low moisture and high temperature environments (7). The ability of storage fungi, particularly *Aspergillus* and *Penicillium* spp., to tolerate relatively low water activity enables them to survive and proliferate under storage conditions that are less favourable for many other microorganisms (1, 2). Fungal infestations in oilseeds lead to a range of qualitative and physical defects, such as seed discolouration, shrinkage, maceration, decreased kernel weight and defective germination. These effects are largely mediated by the enzymatic degeneration of seed stocks, lipid peroxidation and toxic secondary metabolite accumulation. Thus, the colonisation by fungi not only affects seed viability but also presents significant hazards to food and feed safety via mycotoxin contamination. A number of mycotoxigenic and saprophytic fungi, such as *Aspergillus flavus, Aspergillus niger, Fusarium* spp., *Penicillium* spp., *Alternaria* spp., *Rhizopus* spp., *Mucor* spp., *Colletotrichum* spp., *Botrytis* spp. *and Macrophomina phaseolina,* have been reported in oilseed systems. The major mycotoxigenic fungi in oilseeds are depicted in Fig. 1. Among these, *Aspergillus* and *Fusarium* spp. are alarming because they are known to produce active mycotoxins such as aflatoxins and fumonisins. Numerous studies in various

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agroclimatic regions have identified *A. flavus* and *A. niger* as the main storage fungi on oilseeds, especially under warm and humid conditions (8). Groundnuts (*Arachis hypogaea* L.) are among the most important oilseed crops and are particularly vulnerable to both pre- and postharvest fungal infections. Seedborne and soilborne fungal diseases also infect pods in the field and during storage, causing considerable quantitative and qualitative losses. *Aspergillus flavus* is a significant producer of aflatoxins and is therefore a top priority in terms of not only crop yield but also public health. The persistence and the dominance of *Aspergillus* spp. in stored groundnuts indicate that both field and storage management is imperative. Although groundnut, sunflower and sesame have received considerable attention, mycotoxin contamination is also relevant to other economically important oilseed crops, including soybean, rapeseed/canola, flaxseed, castor, safflower and mustard. The occurrence and severity of contamination vary among these crops because of differences in seed composition, cultivar susceptibility, geographical conditions, fungal ecology and pre- and post-harvest management. Soybean and rapeseed/canola can be affected by several mycotoxins, whereas flaxseed, mustard, safflower and other oilseeds may also support toxigenic fungal growth under favourable environmental and storage conditions (3, 4). Therefore, assessments of mycotoxin risk should consider a broader range of oilseed commodities rather than focusing predominantly on groundnut, sunflower and sesame. A comparative crop-based evaluation of the major toxigenic fungi, associated mycotoxins, contamination stages and reported occurrences are presented in Table 1.

The distribution of mycotoxigenic fungi across oilseed crops is not random but reflects interactions among host characteristics, environmental conditions, fungal ecology and postharvest practices (1, 2, 9–20). The predominance of *Aspergillus* spp., particularly *A. flavus*, in several oilseed commodities is associated with their ability to tolerate relatively warm and dry conditions and to colonise stressed or damaged seeds, whereas *Fusarium* spp. are more frequently associated with preharvest infection and crop-specific disease conditions (8–10,12–14,18–20). The occurrence and dominance of individual fungal species can therefore vary according to temperature, moisture availability, drought or heat stress, insect injury, cultivar susceptibility and geographical location (1, 2, 9, 10, 18–20). Importantly, the conventional distinction between “field fungi” and “storage fungi” is not absolute. Although *Fusarium* spp. are commonly associated with field contamination and *Aspergillus* and *Penicillium* spp. with storage environments, some species, particularly *A. flavus*, can colonise oilseeds both before harvest and during storage (8–10, 12–14, 18–20). Thus, mycotoxin contamination should be considered a continuum beginning with field-level fungal establishment and potentially increasing during harvesting, drying, transportation and storage when moisture and temperature conditions become favourable (1, 2, 8–10). This field-to-storage transition is particularly important for oilseeds because inadequate drying, mechanical damage, insect infestation and elevated humidity can facilitate the proliferation of storage-associated toxigenic fungi and subsequent mycotoxin accumulation (8, 9, 12–14, 18–20).

Major mycotoxins affecting oilseeds: Occurrence, diversity and toxicological relevance

Mycotoxins are low-molecular-weight toxic secondary metabolites that are derived from filamentous fungi and are found in numerous agricultural products, including oilseeds. Their introduction into the food chain threatens human and animal health and causes economic losses owing to lower crop value as well as trade barriers (22). The stability of these compounds during processing and storage worsens their potential effects; hence, their use represents an important challenge in oilseed-producing systems.

Aflatoxins: The major mycotoxins in oilseed foods

Aflatoxins, which are the most abundant mycotoxins of oilseeds, are produced mainly by *A. flavus, Aspergillus parasiticus and* similar species. These toxins commonly bioaccumulate in oil-rich resources such as groundnut and sunflower, sesame and vegetable oils (23, 24). The major forms include aflatoxins B1, B2, G1 andG2, with AFB1 being the most toxic and prevalent. Toxicity proceeds in sequence, viz., AFB1 > AFG1 > AFB2 > AFG2 (25). Aflatoxins B1 is categorised as a Group 1 carcinogen by the International Agency for Research on Cancer because of its pronounced hepatocarcinogenic capacity (26). The regulations of countries for aflatoxins vary; in some countries, aflatoxin concentrations of up to 10 µg/kg are permissible for food products, whereas those within the European Union limits are generally 2–4 µg/kg (27, 28). Overstretching these thresholds can cause acute aflatoxicosis and chronic conditions such as liver cancer, immunosuppression and metabolic dysregulation (29).

Crop-specific occurrence of aflatoxins in oilseeds

Owing to their high lipid content and susceptibility to infection before and after harvest, groundnuts (*A. hypogaea* L.) are especially susceptible to aflatoxin contamination. Oil-rich kernels are good substrates for aflatoxigenic fungi, which provides a basis for toxin production. According to reports, up to 93.8 % of *A. flavus* from groundnuts can produce AFB1 and AFB2, indicating the high toxigenic potential of the soil-derived microbiota (30). Analytical surveys indicate that, aflatoxin contamination ranges from 0.5–103.8 µg/kg, which is often greater than the acceptable level (31).

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Table 1. Crop-specific distribution of seed-borne mycoflora in oilseeds

Crop	Dominant fungal spp.	Major mycotoxins	Impact on seeds	References
Groundnut (*Arachis hypogaea*)	*Aspergillus flavus, A. niger, Fusarium oxysporum, F. solani, Macrophomina phaseolina, Rhizoctonia solani, Sclerotium rolfsii*	Aflatoxins (B1, B2, G1, G2), Fumonisins	Seed discolouration, reduced germination, damping-off, pod rot, aflatoxin contamination	(9–16)
Mustard / Brassica (*Brassica campestris*)	*Alternaria brassicae, A. brassicicola, Aspergillus flavus, Fusarium* spp *.*, *Curvularia* spp., *Penicillium* spp.	*Alternaria* toxins (AOH, AME, TeA), Aflatoxins	Seed infection, reduced oil quality, discolouration, poor germination	(17)
Sunflower (*Helianthus annuus*)	*Alternaria alternata, A. helianthi, Aspergillus flavus, A. niger, Fusarium* spp, *Curvularia lunata, Penicillium citrinum, Macrophomina phaseolina*	Aflatoxins, *Alternaria* toxins, Fumonisins	Seed decay, reduced viability, field-to-storage infection, quality deterioration	(18–20)
Sesame (*Sesamum indicum*)	*Macrophomina phaseolina, Fusarium oxysporum, Penicillium chrysogenum, Curvularia lunata, Alternaria dianthicola*	Fumonisins, *Alternaria* toxins	Reduction in sugars, crude fibre, oil content; biochemical deterioration	(21)
General storage mycology (Oilseeds)	*Aspergillus* spp*., Penicillium* spp*., Rhizopus* spp*., Mucor* spp.	Aflatoxins, Ochratoxin A (OTA), Citrinin	Lipid degradation, rancidity, reduced viability, toxin accumulation	(2, 11)

AOH: alternariol; AME: alternariol monomethyl ether; TeA: tenuazonic acid.

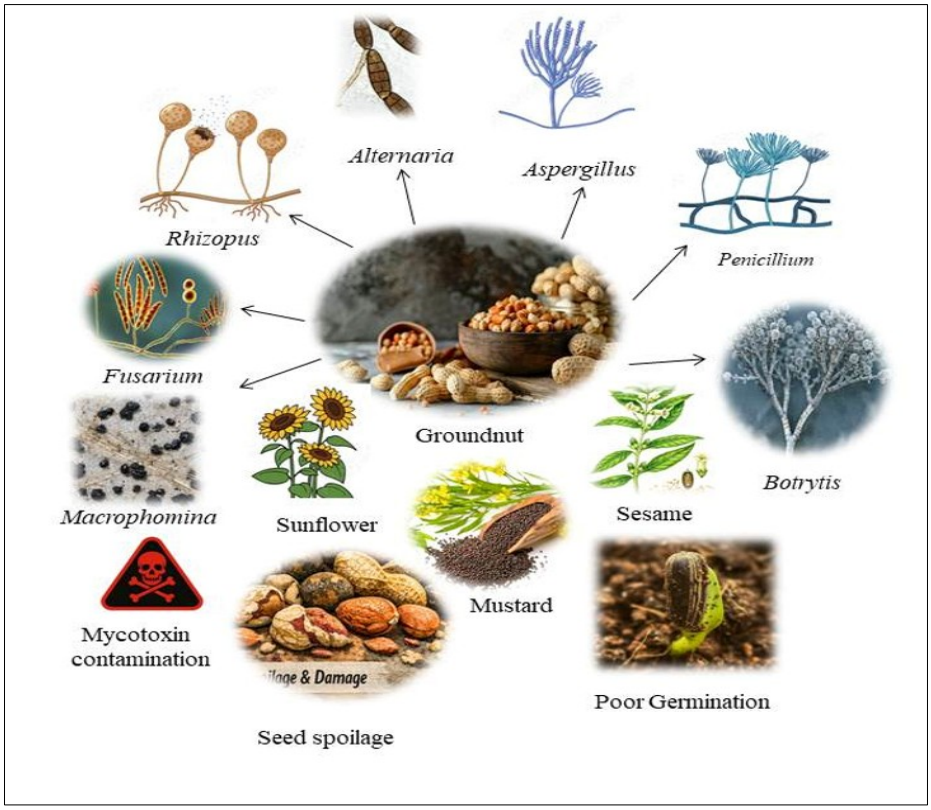

Fig. 1. Major mycotoxigenic fungi in oilseeds.

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Sesame (*Sesamum indicum* L.) is susceptible to aflatoxin contamination, but few studies on this topic have been carried out. The detection of aflatoxin G1 (AFG1) in sesame seeds demonstrates the potential risk of contamination and underscores the need for comprehensive studies on the prevalence, toxin profiles and associated health hazards of mycotoxins in sesame and sesame-based products (32).

Sunflower seeds are highly prone to aflatoxin contamination. The presence of unsaturated fatty acids may regulate fungal metabolism and increase the production of toxins. The AFB1 contents of sunflower seeds and their derivatives, ranging from 0.7–437 µg/kg, have been reported (33, 34). While refining processes should reduce the levels of toxins, aflatoxins may be found in crude and partially refined oils, retaining a significant proportion of oil cakes (35, 36). These findings emphasise the necessity of high-quality raw materials to avoid contamination with edible oils.

Emerging concern of ochratoxins in oilseed systems

Ochratoxins constitute another important class of mycotoxins, that are synthesised primarily by *Aspergillus* and *Penicillium* spp. and are involved in oilseed-associated commodities. Among the ochratoxin family, ochratoxin A (OTA) is the most toxic and occurs widely. Ochratoxins are structurally composed of an isocoumarin moiety linked to an L-phenylalanine group and show the functional groups responsible for toxicity (37). Ochratoxin A is found mainly in cereals, coffee, dried fruits and spices; however, its occurrence in oilseed systems has grained increasing attention (38, 39). Toxicologically, OTA is nephrotoxic, immunosuppressive and carcinogenic. Because of its persistence and accumulation in biological systems, it is a food safety hazard of considerable importance.

Fumonisins: Mycotoxins derived from *Fusarium*

Fumonisins are produced by *Fusarium* spp. such as *F. verticillioides* and *F. proliferatum*, which colonise plant tissues and soil environments. The main fumonisins are FB1, FB2 and FB3, with FB1 being the most abundant and toxic form. These compounds disrupt the metabolism of sphingolipids and cause cell dysfunction and disease in both humans and animals. In addition to *Fusarium*, some strains of *A. niger* can also produce fumonisins (FB2, FB4, FB6), illustrating the ecological diversity of fumonisin-producing fungi. The broad ranges they span in terms of substrates and environments highlight their relevance for industrial farming applications (40).

Co- occurrence of mycotoxins

Mycotoxin contamination in oilseeds should not be considered solely in terms of individual toxins because the co-occurrence of multiple mycotoxins may occur within the same commodity. Aflatoxins, fumonisins, ochratoxins and Alternaria toxins may occur simultaneously, particularly when oilseeds are exposed to multiple toxigenic fungal species or favourable environmental conditions. Such co-contamination is important because the combined toxicological effects may be additive, synergistic, or antagonistic rather than simply equivalent to the effects of each toxin individually (3). Therefore, risk assessment based exclusively on individual mycotoxin concentrations may not fully represent the potential health risk associated with real-world dietary exposure. However, the magnitude and direction of the combined effects depend on the specific toxin combination, dose, exposure duration, biological model and matrix, highlighting the need for multi-mycotoxin surveillance and further toxicological studies in oilseed commodities.

Health risks of mycotoxins: Mechanisms and biological impact

Mycotoxins are toxic secondary metabolites that are produced by filamentous fungi and that become harmful to humans and animals. The majority of exposures occur through the ingestion of food and feed contaminated with mycotoxins causing a range of acute and chronic conditions termed “mycotoxicosis.” The degree of toxicity varies according to the type of mycotoxin, the level and duration of exposure and the susceptibility of the hosts**..** The mechanisms of toxicity and associated biological effects are summarised in Fig. 2 and Table 2.

Aflatoxins: Hepatotoxicity and carcinogenic effects

Aflatoxins, produced primarily by *A. flavus* and *A. parasiticus*, are the most potent natural human carcinogens known (41). The toxic form of AFB1 enters the liver via cytochrome P450 enzymes, where its metabolic activation results inaflatoxin-8,9-epoxide, which interacts with protein and DNA, followed by mutagenesis and hepatocellular carcinoma. While acute aflatoxicosis is associated with significant liver injury, bleeding, edema and mortality, chronic exposure causes more chronic sequelae such as cancer, immunosuppression and growth retardation (42). Epidemiological reports have also associated exposure to aflatoxin with an impaired immune system and growth stunting in children (43, 44). Aflatoxin B1 (AFB1) disrupts carbohydrate, lipid and nucleic acid metabolism in livestock and therefore leads to systemic physiological dysfunction (45). Furthermore, aflatoxin M1, a hydroxylated metabolite of AFB1, is excreted in milk from exposure to contaminated animal feed (46, 47), thus exposing humans to AFB1 as a secondary contact. Aflatoxicosis has been observed throughout many regions, worldwide in both humans and animals (48, 49).

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Table 2. Mechanisms of toxicity and associated biological effects

Toxin	Mechanism of action	Target organ(s)	Associated diseases	References
Aflatoxins (AFB1, B2, G1, G2)	Metabolic activation to epoxide; DNA adduct formation; mutagenesis	Liver, immune system	Hepatocellular carcinoma, aflatoxicosis, immunosuppression	(41–49)
Ochratoxin A (OTA)	Oxidative stress (ROS); protein synthesis inhibition; mitochondrial dysfunction	Kidney, liver	Nephrotoxicity, carcinogenicity, immunotoxicity	(50–59)
Fumonisins (FB1, FB2, FB3)	Ceramide synthase inhibition; sphingolipid disruption	Liver, kidney, nervous system	Esophageal cancer, neural tube defects, pulmonary edema	(40, 60–66)
Alternaria toxins (AOH, AME, ALT, TeA)	DNA binding; oxidative stress; oncogene activation	Gastrointestinal tract, esophagus	Mutagenicity, carcinogenicity	(67–71)

AOH: alternariol; AME: alternariol monomethyl ether; ALT: altenuene; TeA: tenuazonic acid.

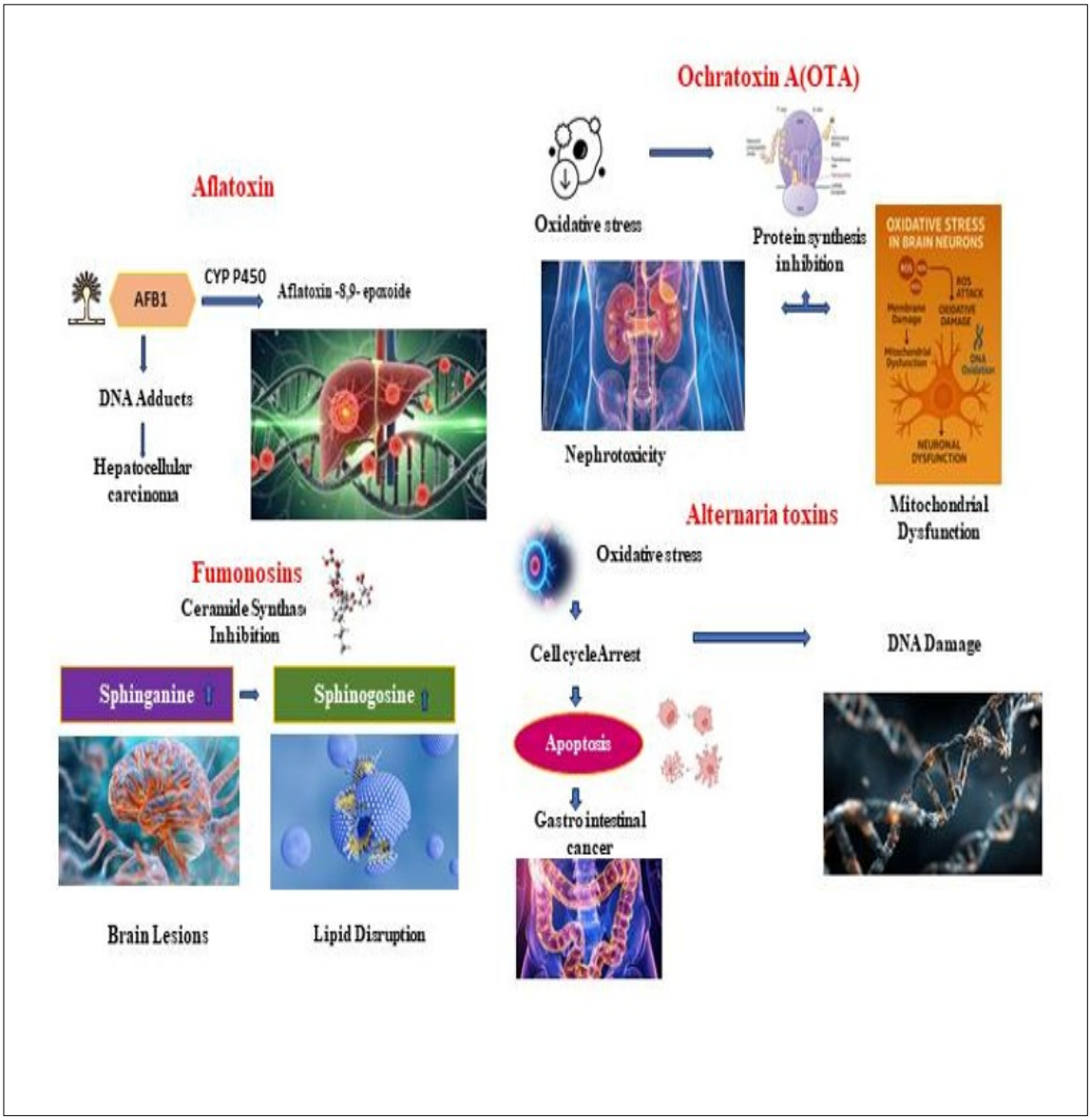

Fig. 2. Mechanisms of toxicity and associated biological effects.

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Ochratoxins: Nephrotoxicity and oxidative stress mechanisms

Ochratoxin A (*Aspergillus* and *Penicillium* forms), a representative nephrotoxic mycotoxin, is classified as a potential human carcinogen (Group 2B) (50). Ochratoxin A has a sustained biological half-life of ~ 35 days which is attributed to its intense binding to plasma proteins, leading to bioaccumulation. The toxicity of OTA results from oxidative stress, the inhibition of protein synthesis, mitochondrial dysfunction and DNA damage (51–55). The increased production of reactive oxygen species (ROS) caused by OTA is able to induce lipid peroxidation and cell damage, especially in renal proximal tubule cells (56), OTA has detrimental effects on detoxification pathways through nuclear receptors, including pregnane X receptor (PXR) and aryl hydrocarbon receptor (AhR) and its ability to suppress antioxidant defence systems that are regulated by transcription factors, particularly Nrf2 (57 –59). The combined effects include nephrotoxicity, hepatotoxicity, immunotoxicity and carcinogenicity.

Fumonisins: Dysregulation of sphingolipid metabolism

Fumonisins, which are produced mainly by *Fusarium* species, are toxic because they block ceramide synthase, an enzyme that helps with sphingolipid metabolism. This disturbance causes an overabundance of sphinganine and sphingosine, resulting in oxidative stress, apoptosis and cell death (60, 61). Fumonisin exposure is linked to serious animal illnesses, as shown by equine leukoencephalomalacia and porcine pulmonary edema (40, 62). In humans, fumonisins are involved in esophageal cancer and neural tube abnormalities (63). The latter is a result of disturbed folate transport secondary to disturbed sphingolipid metabolism (64, 65). Moreover, fumonisin contamination in animal feed is related to hepatocellular apoptosis, renal toxicity and metabolic perturbations, reinforcing its general toxicological significance (66).

Alternaria toxins: Emerging genotoxic risks

Alternaria toxins such as alternariol (AOH), alternariol monomethyl ether (AME), altenuene (ALT), altertoxins, or tenuazonic acid (TeA) are an emerging class of mycotoxins with extensive genotoxic and carcinogenic potential (67). Experimental evidence has shown that AOH and AME can prompt mutagenesis, adhere to DNA and activate oncogenes such as c-Hras and c-myc to produce changes in cells and the formation of tumor cells (68–71). Epidemiological studies suggest a potential association between *Alternaria* contamination and the incidence of oesophageal cancers in certain high-risk areas.

Standards and surveillance regulators of mycotoxins

The Food Safety and Standards Authority of India (FSSAI) is responsible for establishing food safety standards and monitoring mycotoxin contamination in India. The agency established limits (MLs) for major mycotoxins in food matrices and maintains a monitoring programme for both domestic and imported food supplies. Some revised recommendations for mycotoxin analysis and regulatory thresholds have been integrated into national food safety regulations (72, 73). India has a wide network of well-accredited laboratories under the Food Safety and Standards (FSS) Act, 2006, for enforcement purposes. This encompasses food testing laboratories accredited by ISO/IEC 17025:2017 that are nationwide, guaranteeing consistent and reliable analytical methods. The NFLs in Ghaziabad, Kolkata and Mumbai are critical for routine testing and surveillance (74). A network of over 200 National Accreditation Board for Testing and Calibration Laboratories (NABL)-accredited laboratories facilitates regional testing in these zones. Referral laboratories are used to process disputed or noncompliant samples, whereas National Reference Laboratories (NRLs) handle method development, validation and proficiency testing. The data-based solution focuses on these agencies as a whole to ensure accuracy in analysis and consistency of testing procedures across the food chain with regulatory compliance. Despite the existence of an overarching regulatory framework, mycotoxin management continues to face several challenges. These include variations in contamination levels driven by climate change, the lack of real-time monitoring tools and insufficient awareness and implementation of preventive measures at both the farm and storage levels. The effects of climate change on mycotoxin contamination are mediated through complex interactions among temperature, water availability, relative humidity, drought stress and atmospheric CO_2 and these responses vary among fungal species and oilseed production systems. Increased temperature can alter fungal community composition and favour thermotolerant species such as *A. flavus*, whereas drought and water stress can increase crop susceptibility under suitable temperature and water-activity conditions, stimulate aflatoxin biosynthesis. In contrast, increased moisture and humidity may favour other toxigenic fungi, including *Fusarium* and some *Penicillium* species, demonstrating that climate-driven changes in mycotoxin risk are toxin- and species specific. Elevated CO_2 can further modify fungal physiology and secondary metabolism; experimental studies have shown that elevated CO_2 combined with high temperature and water stress can increase the expression of aflatoxin biosynthetic genes and AFB_1 production in *A. flavus*. Therefore, climate change should not be considered simply as a general increase in fungal growth, but rather as a shift in fungal community structure, host susceptibility and toxin-biosynthesis pathways resulting from interacting environmental factors (60, 61). Moreover, due to the use of preventive methods, it is necessary to better

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incorporate predictive tools and risk assessment models. Ongoing policy directions include enhancing surveillance systems for digital monitoring and improving farmer-level adoption of best practices and better detection facilities at the regional and local levels. The combination of climate-resilient strategies with biological control activities is important for controlling mycotoxin risk to mitigate the risks associated with environmental change (74). The permissible limits of major mycotoxins in oilseeds and oilseed products are listed in Table 3.

Detection methods for mycotoxins

The detection and quantification of mycotoxins have advanced significantly over the last 20 years because of the demands of increased sensitivity, selectivity and adherence to international regulatory requirements. Over the years, India's analytical approaches have progressed from traditional immunoassay-based methods to chromatographic and mass spectrometry-based methods, which reflects technological advancements and enhanced regulatory requirements. The evolution of mycotoxin analysis techniques is depicted in Fig. 3.

Immunoassay-based techniques for early detection

Prior to 2006, mycotoxin testing in India was conducted mainly via immunochemical methods, including enzyme-linked immunosorbent assays (ELISAs). While the ELISA method provides rapid screening, it is also limited by matrix interference, limited selectivity and a risk for false-positive and false-negative results (77). Because of these limitations, ELISA is primarily used for screening rather than confirmatory analysis.

Chromatographic techniques

Regulatory frameworks around the world such as, the European Commission (EC) Regulation 401/2006 encouraged robust analytical approaches and a standardisation of analytical methods. The proliferation of chromatographic techniques, especially high-performance liquid chromatography (HPLC) with fluorescence detection (FLD) and liquid chromatography-tandem mass spectrometry (LC-MS/MS), in India has helped laboratories meet export compliance requirements for commodities such as groundnuts and processed products. These techniques provide superior sensitivity, specificity and reproducibility, making it possible to count mycotoxins at trace levels. Fluorescence-based detection has been limited to specific toxins, including aflatoxins and OTA; therefore, LC-MS/MS was adopted for multiple mycotoxin analyses throughout heterogeneous food matrices (77).

Advanced multiresidue and high-resolution techniques

The use of LC-MS/MS was a milestone in mycotoxin analysis, allowing the simultaneous detection of multiple toxins, achieving high analytical accuracy and low limits of quantification. Higher-end techniques, including UHPLC-QqQ-MS/MS, have limits of quantification as low as 0.5–1 µg/kg while achieving considerable recovery and precision over complex matrices such as edible oils. Some examples include QuEChERS and liquid–liquid extraction techniques, which have greatly improved analytical performance through a significant reduction in matrix interference, particularly in lipid-rich oilseed samples. These advances have made it possible to perform thorough multi-class mycotoxin profiling with the use of aflatoxins, fumonisins, ochratoxin A and zearalenone (77). However, the choice of analytical method should be determined by the intended application rather than analytical sensitivity alone. Immunoassays such as ELISA are advantageous for rapid and relatively inexpensive screening of large numbers of samples, but matrix interference and limited selectivity can restrict their use for definitive quantification (77). High-performance liquid chromatography-fluorescence detection (HPLC-FLD) provides reliable quantitative determination of selected mycotoxins and is more accessible than high-resolution mass spectrometry, but its applicability is restricted by the availability of suitable fluorescence responses and derivatisation requirements for some toxins. In contrast, LC-MS/MS and UHPLC-QqQ-MS/MS provide superior sensitivity, specificity and multi-mycotoxin capability and are therefore particularly valuable for confirmatory analysis and regulatory surveillance; however, their high instrumentation and maintenance costs, complex sample preparation and requirement for skilled personnel limit their routine use in resource-limited or field settings (77). Consequently, a tiered analytical strategy combining low-cost rapid screening with laboratory-based confirmatory methods may provide a more practical balance between analytical performance, cost and throughput.

From a cost-benefit perspective, no single detection method is optimal for all applications. Enzyme-linked immunosorbent assay and other immunoassays generally offer advantages in terms of lower equipment requirements, rapid analysis and high sample throughput, making them suitable for preliminary screening. High-performance liquid chromatography-fluorescence detection (HPLC-FLD) provides a useful balance between analytical reliability and instrumentation cost for selected mycotoxins, whereas LC-MS/MS offers the greatest analytical scope and multi-mycotoxin capability but requires substantially greater capital investment, maintenance, specialised personnel and laboratory infrastructure (77). Emerging biosensors and portable devices may reduce per-test costs and enable decentralised testing, but their initial development, validation, calibration and quality-control requirements should also be considered. Therefore, cost-benefit assessment should consider not only instrument and consumable costs but also sample throughput, analysis time, personnel requirements, sensitivity, confirmatory capability, portability and the consequences of false-positive or false-negative results.

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Table 3. Permissible limits of major mycotoxins in oilseed and oilseed products

Mycotoxin	Producing fungi	Major oilseeds affected	Maximum permissible limit (µg/kg)	Regulatory authority	Reference
Aflatoxin B1	*Aspergillus flavus, A. parasiticus*	Groundnut, sunflower, sesame, soybean	5	FSSAI	(74)
Total aflatoxins (B1 + B2 + G1 + G2)	*Aspergillus* spp.	Oilseeds and oilseed products	15	FSSAI	(74)
Ochratoxin A (OTA)	*Aspergillus* spp., *Penicillium* spp.	Oilseeds and processed products	5	European commission	(75)
Fumonisins (FB1 + FB2)	*Fusarium verticillioides, F. proliferatum*	Occasionally oilseeds and oilseed products	1000–4000	European union	(75)
Alternaria toxins (AOH, AME, TeA)	*Alternaria* spp.	Sunflower, sesame, Mustard seeds	No harmonised limit	EFSA	(76)

AOH: alternariol; AME: alternariol monomethyl ether; TeA: tenuazonic acid.; EFSA: European Food Safety Authority; FSSAI: Food Safety and Standards Authority of India.

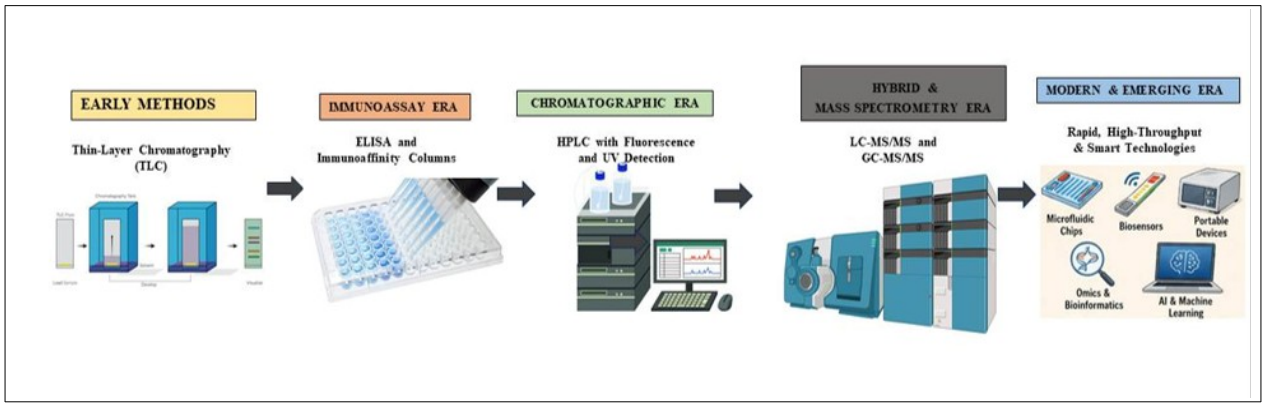

Fig. 3. Evolution of mycotoxin analysis techniques.

Standardisation and regulatory harmonisation

The FSSAI was established in 2011 and was a step toward standardising mycotoxin analysis across the country. The authors implemented maximum limits (MLs) for significant mycotoxins and standardised analytical protocols in accordance with international standards. One such landmark was the MoU between FSSAI and Association of Official Analytical Chemists (AOAC INTERNATIONAL) which facilitated access to the official methods that had been verified (as well as encouraged harmonisation of analytical practices across laboratories). NABL-qualified laboratories use AOAC or National Referral Laboratory - ICAR-National Research Centre for Grapes (NRL-NRCG) validated methods of this nature and therefore standardise test results. Method validation protocols include comprehensive assessments of recovery, precision, reproducibility and sensitivity, interlaboratory validation (ILV) in multiple laboratories. To ensure compliance and reliability, analytical methods are required to reach quantification limits below regulatory MLs (78).

Emerging technologies and future directions

Recent developments have extended biosensor technology toward portable and smartphone-integrated platforms for onsite mycotoxin monitoring. Miniaturised electrochemical sensors, lateral-flow assays, paper-based devices and smartphone-assisted optical systems can provide rapid screening with reduced equipment requirements and improved field portability. Smartphone integration can further enable image acquisition, signal processing, data storage and transmission, creating opportunities for decentralised monitoring at farms, storage facilities, markets and processing units. However, these emerging systems still require rigorous validation against reference chromatographic methods, standardised calibration procedures, assessment of matrix effects and evaluation of their performance across diverse oilseed matrices before they can replace laboratory-based confirmatory methods (77).

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While these methods have made great strides in both the application and feasibility, chromatographic techniques, more importantly LC-MS/MS, still have merit as the standard method for confirmatory analysis, not only due to their better precision but also their capabilities (79). Future research in mycotoxin analysis may explore high-throughput real-time detection systems, the integration of portable devices that can be used for field-level monitoring and the use of artificial intelligence for predictive risk assessment. As we remain close to the worldwide level of harmonisation and analytical infrastructure, maintaining the safety of food supplies and promoting international trade are important.

Prevention and detoxification of mycotoxins

Preventing mycotoxin toxicity

The most effective strategies for mycotoxin control still rely on preventive tactics. Before harvest, the use of resistant cultivars, crop rotation, fertilisation and pest management in combination with proper pest management effectively reduce fungal infection. Drought and high temperature are environmental factors for mycotoxigenic fungi, which stresses the need for a climate-adapted agricultural approach. The best practices such as timely harvesting and minimal mechanical damage are critical for inhibiting the penetration of fungi and colonisation. Postharvest measures (e.g., drying quickly to < 13–14 % moisture, proper storage conditions and sanitation) additionally hinder fungal proliferation and toxin production. Biological control methods, specifically those involving atoxigenic strains of *A. flavus,* have demonstrated potential for aflatoxin control via competitive exclusion (80).

Detoxification

When contamination occurs, detoxification measures are used to lower the levels or reduce the toxicity of mycotoxins. The promising methods include separation, cleaning, dehulling, sorting, or dehusking but this rarely takes us to the point of getting rid complete toxin elimination because it remains stable. Methods such as ammoniation, ozone, organic acid oxidation agents and many different chemical detoxifiers can rapidly decompose mycotoxins. However, these treatments can affect nutritional quality and acceptance by consumers, which restricts their utilisation in food systems (3). Detoxification of mycotoxins is depicted in Fig. 4.

Processing influence on mycotoxins in oilseeds

The processing of oilseeds and oilseed derivatives has a very important influence on the fate of mycotoxins. However, the degree of reduction in mycotoxins relies on the toxin type, processing route and physicochemical characteristics of the food matrix. Although some techniques can reduce mycotoxin levels to a considerable extent, complete elimination is infrequent because many of them are very stable. The influence of processing on the mycotoxins in oilseeds is listed in Table 4.

a) Mechanisms of aflatoxin degradation by physical and advanced processing

Moderate heat stability is observed for aflatoxins, despite their high reactivity to heat, which can be reduced by physical, chemical and advanced processing methods. Ultraviolet C (UV-C) irradiation, ozone treatment and organic acids (such as citric acid) can be combined in nonthermal processes and are more effective methods for detoxification. For example, integrated treatments utilising UV-C, citric acid and ozone have achieved degradation efficiencies of over 90–99 % for major aflatoxins (86). Photocatalytic detoxification using titanium dioxide (TiO_2) is also relatively effective and has been shown to result in > 99 % degradation of aflatoxins in groundnut oil in a short time (minutes) without deteriorating the quality of the oil (87). Similarly, the amount of AFB1 in groundnut oil can decrease by ~ 99 % after ultraviolet light-emitting diode (UV-LED) treatment, but this decrease is not significantly affected by some physicochemical features (81). However, shallow penetration depth, variability of exposure and operation limitations exist, which inhibit application of UV as a broad-based method. These sensors employ relatively small amounts of solvent and are used for monitoring rather than detoxification. Other emerging biosensing technologies, including aptamer-based sensors, will improve detection sensitivity but are more for monitoring use than detoxification (82, 83). Critical evaluations of reported detoxification efficiencies and reported detoxification efficiencies for mycotoxin-contaminated oilseeds vary substantially among studies and should therefore be interpreted cautiously. Differences in food matrix composition, initial mycotoxin concentration, toxin type, treatment intensity, exposure time, temperature, moisture content and analytical methodology can influence the apparent reduction in toxin concentration (83, 84). In particular, the food matrix and treatment conditions can substantially affect the efficacy of mycotoxin degradation, making direct comparison of reported percentages difficult (84). Furthermore, a reduction in the concentration of the parent mycotoxin does not necessarily indicate complete detoxification, because transformation products may remain and their toxicological safety requires evaluation (85). Therefore, reported values such as 90 % or > 99 % reduction obtained under different experimental conditions should not be interpreted as evidence that one technology is universally superior. Overall, current evidence indicates that detoxification efficiency is matrix- and process dependent and standardised treatment conditions, validated analytical methods, identification of degradation products and toxicity assessment are needed for meaningful comparisons and reliable industrial applications (83–85). Mycotoxigenic fungi in

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oilseeds: occurrence, risk and sustainable management strategies are depicted in Fig. 5.

Table 4. Influence of processing on mycotoxins in oilseeds

Processing method	Target mycotoxin	% Reduction (Approx.)	Limitations	References
UV-C + citric Acid + ozone	Aflatoxins (AFB1, B2, G1, G2)	> 90–99 %	Limited penetration; scalability issues	(81)
Photocatalysis (TiO_2 + UV)	Aflatoxins (AFB1, AFB2)	≥ 99 %	Requires specialised equipment; cost	(82)
UV-LED treatment	Aflatoxin B1	~ 99 %	Uneven exposure; shallow penetration	(83)
UV-C radiation	Multiple mycotoxins	Moderate–High	Low penetration; safety concerns	(83)
Extrusion (> 150–175 °C)	Fumonisins	60–90 %	Formation of masked toxins	(40)
Roasting / Frying	Fumonisins	Moderate–High	Incomplete detoxification	(40)
Oil refining	Ochratoxin A	Significant (partial)	Incomplete removal; residues remain	(84)
Alkaline treatment	Ochratoxin A	Moderate–High	Formation of byproducts	(84)
Refining (Sunflower oil)	*Alternaria* toxins	Significant	Redistribution into byproducts	(85)
Extrusion / Thermal	*Alternaria* toxins	Moderate	Depends on processing conditions	(85)
Sorting / Cleaning / Dehulling	Multiple mycotoxins	Low–Moderate	Only physical removal	(40)

UV: ultraviolet; UV-LED: ultraviolet light-emitting diode; UV-C: ultraviolet-C; TiO2: titanium dioxide.

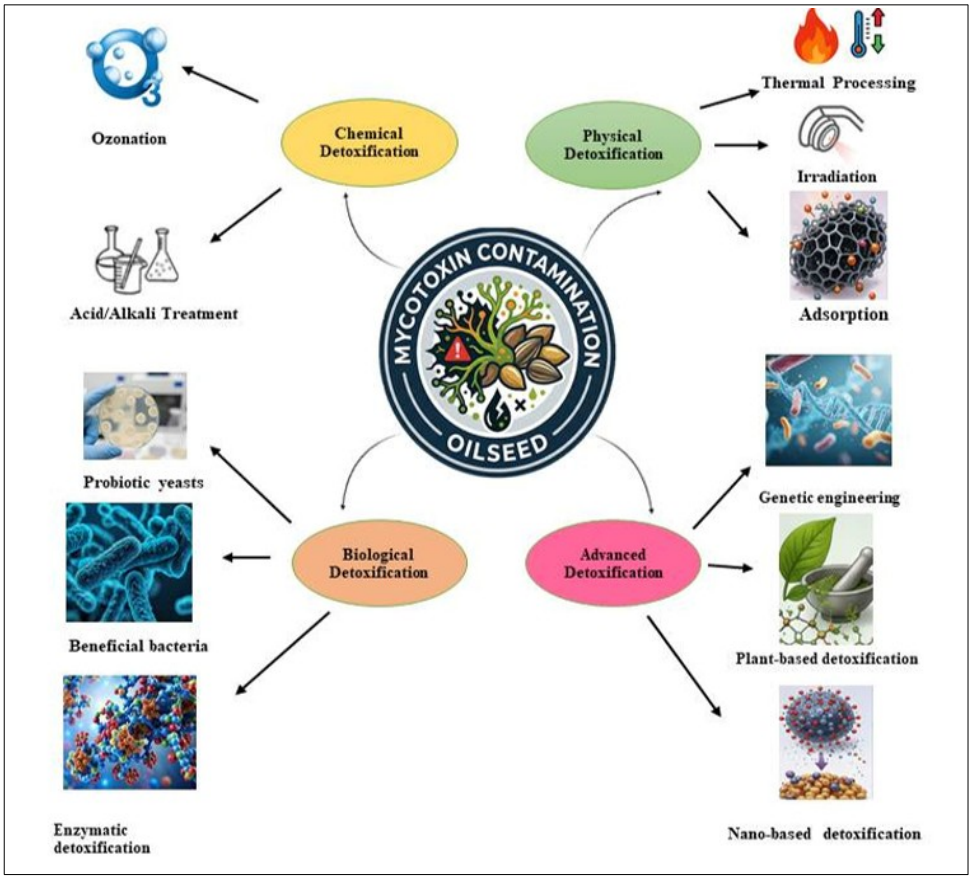

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Fig. 4. Mycotoxin detoxification techniques.

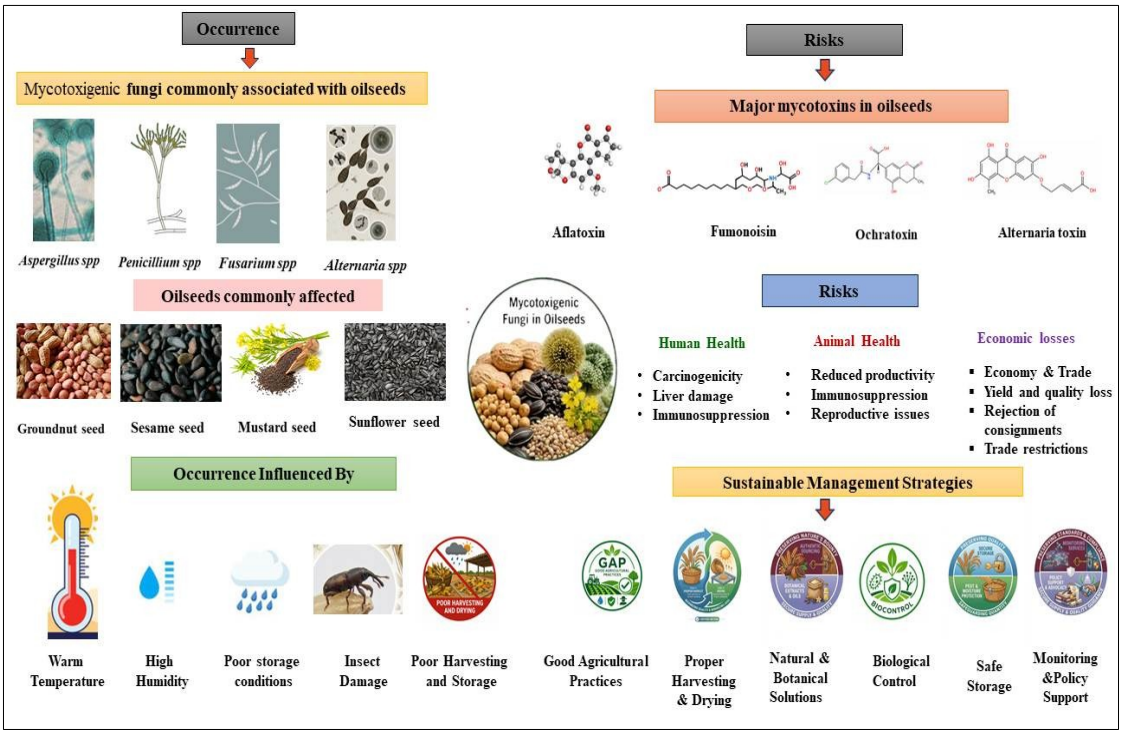

Fig. 5. Mycotoxigenic fungi in oilseeds: Occurrence, risk and sustainable management strategies.

b) Fumonisins: Stability and transformation during processing

Thermal processing, however, may modify fumonisin derivatives via transformation with reducing sugars. These masked forms can present a challenge to risk assessment as high biological activity can be maintained even in the absence of detectable levels. In oilseed processing, fumonisins are regularly regrouped rather than decomposed and the physical actions of dehulling and milling determine the partitioning between different fractions in these fractions (40).

c) Ochratoxin A: Partial reduction in refining with degradation

Ochratoxin A (OTA) has excellent thermal stability and is reduced in some amounts during conventional processes. Ochratoxin A can also be reduced in oilseed refining by degumming, neutralisation, bleaching and deodorisation. Alkaline conditions during deacidification can drive hydrolysis of the OTA lactone ring and the conversion to less noticeable OTA (OP-OTA) in the form of open-ring OTA. Although these processes decrease OTA levels in the oil fraction, the toxins do not need to be fully removed and any remaining toxins may be present in secondary products, such as soap stock. Thus, monitoring refined oils and waste residues during processing is important for proper risk assessment (84).

d) *Alternaria* toxins: Reduction during refining and thermal processing

Alternaria toxins such as AOH and TeA can be diminished in oilseed processing, especially through refining and high-temperature treatment. Refining processes considerably decrease toxin content in edible oils, presumably by clearing it, degrading it, or diverting its contents into secondary compounds. Extrusion and other thermal processing processes have also been reported to decrease *Alternaria* toxin content; however, in general, such elimination is not complete. The reduction rate is moderated in degree of extent by the level of processing: temperature, moisture and duration (85).

Biological detoxification of mycotoxins

The effectiveness of biologics on the underlying mechanisms of toxin removal or transformation. Microbial detoxification may occur through enzymatic biotransformation, in which microbial enzymes modify or degrade mycotoxin molecules into products with reduced toxicity. In contrast, adsorption-based approaches primarily remove mycotoxins through physical and chemical interactions with the surface of the adsorbent, including hydrogen bonding, hydrophobic interactions, ionic interactions and pore trapping, thereby reducing toxin bioavailability without necessarily destroying the parent molecule. Biological detoxification and microbial biocontrol approaches for sustainable

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mycotoxin management in oilseed systems are listed in Table 5.

Table 5. Biological detoxification and microbial biocontrol approaches for sustainable mycotoxin management in oilseed systems

Approach	Mechanism of action	Target mycotoxin	Reported efficacy (%)	Major advantages	Key limitations	References
Microbial biocontrol	Competitive exclusion of toxigenic fungal strains and suppression of aflatoxin biosynthesis	Aflatoxigenic *A. flavus*, aflatoxins	70–95	Eco-friendly, field applicable, effective in reducing toxin contamination	Environmental variability and strain adaptation may affect performance	(6, 80, 88)
Probiotic bacterial detoxification	Adsorption, biodegradation and enzymatic transformation of toxins	Aflatoxins, ochratoxins, fumonisins	60–90	Food-safe organisms, minimal nutritional loss	Strain-specific efficacy and limited industrial-scale validation	(3, 6, 88)
Yeast-based detoxification	Binding of mycotoxins through cell wall polysaccharides (β-glucans and mannoproteins)	Aflatoxins, fumonisins, ochratoxin A	50–85	GRAS status, easy incorporation into feed and food systems	Toxin binding may be reversible under gastrointestinal conditions	(3, 6, 62)
Enzymatic detoxification	Biotransformation of mycotoxins into less toxic metabolites	Aflatoxins, fumonisins, zearalenone, ochratoxins	70–95	High specificity and targeted detoxification	High production cost and enzyme instability	(6, 65, 88)
Fungal biocontrol agents	Antagonism, nutrient competition and antifungal metabolite production	*Aspergillus, Fusarium, Penicillium* spp.	60–85	Reduces fungal growth and toxin production	Variable efficacy under field conditions	(6, 80)
Microbial consortia	Synergistic biodegradation and toxin sequestration	Multiple mycotoxins	70–95	Broad-spectrum detoxification potential	Standardisation and commercialisation challenges	(6, 88, 89)
Microbiome engineering	Manipulation of microbial ecology to suppress toxigenic fungi	Multiple toxigenic fungi	Experimental	Sustainable and long-term suppression strategy	Limited field-level evidence	(88, 90)

Plant-based detoxification of mycotoxins

Owing to their eco-friendliness, biodegradability and consumer acceptance of alternatives to synthetic chemical treatments, plant-based detoxification strategies have attracted significant interest (91, 92). A variety of plant extracts and essential oils, including those obtained from clove (*Syzygium aromaticum*), cinnamon (*Cinnamomum verum*), thyme (*Thymus vulgaris*), oregano (*Origanum vulgare*), neem (*Azadirachta indica)* and turmeric (*Curcuma longa*), have been shown to inhibit the growth of mycotoxigenic fungi such as *Aspergillus, Fusarium and Penicillium* species (92, 93).

The antifungal activities of these plant-derived compounds have been attributed to bioactive constituents such as eugenol, thymol, carvacrol, curcumin and various phenolic compounds that can disrupt fungal cell membranes, hinder cell metabolism and inhibit mycotoxin biosynthetic pathways (91, 93). Some phytochemicals might also directly interact with the molecules of mycotoxins and alter their structure and bioavailability, reducing their toxicity and thus also contributing to detoxification in addition to growth inhibition (91). However, plant detoxification efficacy varies according to the plant source, extraction method and concentration as well as the storage environment and food matrix character, which are crucial factors. Plant-derived materials and bioactive compounds may contribute through adsorption, antioxidant activity, inhibition of fungal growth, or interference with toxin biosynthesis. Importantly, an apparent reduction in the concentration of the parent mycotoxin should not automatically be interpreted as complete detoxification because transformation may generate degradation metabolites whose toxicity and stability require evaluation. Therefore, mechanistic confirmation of toxin degradation, identification and characterisation of transformation products and assessment of their toxicological significance are essential for establishing the safety and practical effectiveness of detoxification technologies.

Nanotechnology-based detoxification of mycotoxins

For mycotoxin detoxification, nanotechnology techniques have emerged as effective approaches

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because of their large surface area, high adsorption capacity and tunable physicochemical properties, which allow the effective binding and elimination of mycotoxins from contaminated food and feed matrices (94, 95). Magnetic nanoparticles, graphene oxide, carbon nanotubes, nanoclays and chitosan nanoparticles strongly adsorb key mycotoxins, such as aflatoxins, OTA, fumonisins and zearalenone. These nanomaterials inhibit toxin bioavailability and toxicity via adsorption and sequestration functions (94, 95). Another benefit of using magnetic nanomaterials is that they can be retrieved easily from treated food systems with an external magnetic field, thereby promoting toxin removal and adsorbent reuse with minimal processing losses (95). Despite their high adsorption efficiency and selectivity, the application of nanomaterials in food detoxification faces important safety and translational challenges. The potential migration of nanoparticles into food, nanoparticle toxicity, environmental accumulation and the fate of residual nanomaterials after treatment require systematic assessment before food applications can be widely adopted. In addition, differences in nanoparticle composition, size, surface properties, dose and food matrix interactions may influence both detoxification performance and safety. Large-scale implementation also requires reproducible manufacturing, recovery or removal of nanomaterials, cost-effective processing, standardised validation protocols and appropriate regulatory approval. Therefore, the high detoxification efficiency reported under laboratory conditions should not be considered sufficient evidence for commercial application and long-term toxicological, environmental, technological and economic evaluations are required (94–96). Although they have great potential, the concerns of nanoparticle toxicity, environmental accumulation and their migration into food products are still pending guidelines that outline their possible applications in food processing (94, 95).

Comparison of conventional and novel methods for mycotoxin detoxification

Mycotoxin detoxification methodologies have undergone considerable growth, evolving from traditional physical and chemical methods to novel biological-based and nanotechnology interventions. All categories have unique advantages and disadvantages in terms of efficiency and specificity as well as safety and in their applicability to different kinds of food matrices. A comparative analysis of conventional and novel detoxification methods is presented in Table 6. Thus, detoxification efficiency alone should not be used as the principal criterion for selecting a treatment technology. A method achieving a high percentage reduction under laboratory conditions may have limited practical value if it causes nutritional deterioration, generates potentially toxic transformation products, requires high energy or reagent inputs, or cannot be scaled economically (78, 80). Recent reviews emphasise the importance of evaluating degradation mechanisms, product safety, food quality and industrial feasibility alongside toxin reduction (78, 80). Therefore, comparative assessment of detoxification technologies should consider efficacy, matrix compatibility, safety, nutritional quality, cost, scalability, environmental impact and regulatory acceptance rather than relying solely on the reported percentage reduction (78, 80). A comparative evaluation of these detoxification approaches indicates that no single method provides an optimal combination of efficacy, safety, nutritional preservation, cost and scalability. Physical approaches such as sorting, cleaning and dehulling are relatively simple and can reduce contamination by removing highly contaminated fractions, but their effectiveness is generally low to moderate and they cannot eliminate toxins that have penetrated into the kernel matrix (40). Thermal processing can be readily incorporated into conventional processing systems, but its effectiveness depends on the thermal stability of individual mycotoxins and processing conditions and complete detoxification is rarely achieved (40, 84, 85). Chemical treatments such as ammoniation can promote effective toxin degradation but may generate residual compounds and raise concerns regarding nutritional quality, consumer acceptance and regulatory compliance (80). Biological detoxification offers greater environmental compatibility and may preserve nutritional quality, but its effectiveness can vary with microorganisms, enzymes or substrates and requires further validation for large-scale application (96). Nanotechnology-based approaches provide high adsorption capacity and targeted toxin removal, but their practical application remains constrained by cost, scalability, potential nanoparticle toxicity, environmental concerns and regulatory uncertainty (94–96). Therefore, the selection of a detoxification strategy should consider not only the reported percentage reduction but also the matrix compatibility, product quality, safety, processing requirements, economic feasibility and scalability.

Traditional detoxification remediation and other methods

The traditional methods for detoxification are physical separation (sorting and dehulling), thermal treatment and chemical treatments (such as ammoniation and the addition of organic acids). Such methods have been commonly utilised to further reduce contamination by many major mycotoxins such as aflatoxins, ochratoxins, fumonisins, trichothecenes and deoxynivalenol. Physical operations increase the purity of mycotoxins by removing contaminated fractions but do not remove pollutants that are already present within the kernel matrix. Thermal treatment is constrained by the intrinsic heat stability of many mycotoxins and can degrade only some parts of the toxins under standard processing conditions. Chemical detoxification (ammonia treatment) is an efficient way to decompose some toxins, but it has the potential to form residual compounds and thus compromises the quality of nutrition and consumer acceptance. In addition, regulatory limitations and growing consumer demands for chemical residues restrict the dissemination of these methods of utilisation in various food environments (80). Therefore,

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conventional practices are frequently regarded as means of reducing, rather than eliminating, the chemical constituents as they are completely detoxified.

Table 6. Comparative analysis of detoxification methods

Category	Method	Mechanism of action	Detoxification efficiency (%)	Major advantages	Key limitations	References
Conventional approaches	Sorting, cleaning and dehulling	Physical removal of contaminated seeds and outer layers	20–60	Simple, low-cost, easy to implement	Ineffective against internally distributed toxins	(80)
	Thermal processing	Degradation of toxins through heat treatment	10–50	Commonly used in food processing	Limited effectiveness due to heat-stable mycotoxins	(80)
	Ammoniation	Chemical modification and detoxification of toxins	50–90	Highly effective against aflatoxins	Possible chemical residues and nutrient loss	(80)
	Organic acids/Ozone treatment	Oxidative degradation of mycotoxins	40–80	Improved detoxification efficiency	May affect sensory and nutritional quality	(80)
Emerging technologies	Biological detoxification	Microbial degradation, adsorption, or transformation of toxins	60–95	Eco-friendly and highly specific	Slow process and scale-up challenges	(96)
	Enzymatic detoxification	Enzyme-mediated breakdown of toxin molecules	70–95	Target-specific detoxification	High cost and enzyme stability issues	(96)
	Nanotechnology-based adsorbents	Adsorption of toxins using nanomaterials	70–99	Very high efficiency and rapid action	Regulatory and safety concerns	(96)
	Nano-biosensors	Integrated detection and potential removal of toxins	Variable	Real-time monitoring and high sensitivity	Largely experimental	(96)

Novel detoxification approaches

Detoxification techniques, including biological and nanotechnology-based treatments, also increase specificity and safety, while biological detoxification is also promoted from a biological perspective. For biological detoxification, microorganisms such as *Lactobacillus* spp. and *Aspergillus* spp. are employed to further degrade mycotoxins into less toxic and nontoxic metabolites via enzymatic transformation. These methods are environmentally friendly and maintain the nutritional quality of foods. Selected nontoxigenic strains of *Aspergillus*, particularly atoxigenic *A. flavus* strains, have been investigated as biological control agents for reducing aflatoxin contamination through competitive exclusion of toxigenic strains (89, 96) Nanotechnology-based methods are a new approach that uses nano-adsorbents and materials with the ability to selectively bind mycotoxins. They have a high surface area, strong binding efficiency and targeted detoxification. Furthermore, biosensor-based nanomaterials can perform simultaneous toxin detection and removal. Although promising, new techniques suffer significant bottlenecks such as high working costs, scalability and uncertain regulation. The use of these methods on a large scale is challenging, as there are no standardised validation protocols and limited field-level applications (96).

Future perspectives on sustainable mycotoxin control in oilseeds

The increasing prevalence of mycotoxigenic fungi and related mycotoxin contamination in oilseed systems underscores the need for intelligent, sustainable and climate-dependent management approaches. Future research could focus on prediction and precision-based prevention to mitigate contamination risks in oilseed production and the value chain. Climate change, especially increased temperature, drought stress and altered relative humidity patterns, is likely to change

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fungal ecology and promote the predominance of fungi with toxin-producing traits, such as *A. flavus* and *Fusarium* spp. and in turn, the risk of contamination in oilseeds. Therefore, predictive ecological modelling, climate-based forecasting and geographic information system (GIS) should be developed to support early warning technologies for mycotoxin outbreaks and contamination hotspots (60, 61, 88). The improvement of fast, handheld, real-time detection technologies can limit the spread of mycotoxins in stored products. Chromatographic techniques, such as HPLC or LC–MS/MS, are considered the gold standard for the determination of sensitive mycotoxins but are typically costly and laboratory specific, limiting their general use in the field. These applications should be supported by portable biosensors, aptamer-based assays, nano biosensors and smartphone-assisted detection systems that can multiplex and provide real-time monitoring of mycotoxins in oilseed production and storage environments. Such technologies would dramatically enhance surveillance and regulatory-monitoring systems (4, 77, 79). Biological detoxification and microbial biocontrol approaches are relevant because of concerns about chemical residues and environmental sustainability. The application of atoxigenic strains of *A. flavus*, microbial antagonists, detoxification mechanisms using enzymes and microbiome-assisted strategies has demonstrated the potential to block fungal colonisation and toxin accumulation. However, there is a need for extended research focusing on strain stability, formulation improvement, field-scale validation and regulatory clearance for commercialisation (6, 85, 89) Several other critical research gaps should also be addressed to improve the practical relevance of mycotoxin management in oilseed systems. First, although mycotoxin contamination is associated with considerable yield, quality and economic losses, crop-specific quantitative assessments remain limited. Future studies should estimate losses at the farm, storage, processing and market levels for major oilseed crops to distinguish direct production losses from costs associated with testing, rejection, disposal and detoxification (3, 78). Second, climate-change assessments should move beyond general predictions and develop region-specific risk projections for major oilseed-producing regions. Such models should integrate temperature, drought, relative humidity, fungal ecology, crop susceptibility and historical contamination data to identify geographical hotspots and future shifts in mycotoxin risk (60, 61). Third, the occurrence and significance of masked or modified mycotoxins in oilseeds and their processed products require greater attention. Processing may transform mycotoxins into modified forms that are not detected by conventional analytical methods but may retain biological activity or release the parent toxin under gastrointestinal conditions (40). Therefore, future risk assessments should incorporate both free and modified forms of mycotoxins. Fourth, the health implications of simultaneous exposure to multiple mycotoxins remain insufficiently understood. Cooccurring mycotoxins may produce additive, synergistic, or antagonistic effects; therefore, risk assessment based solely on individual toxins may underestimate or overestimate the actual hazard. Multiple mycotoxin surveillance and mechanistic toxicological studies are needed to clarify these interactions in oilseed matrices (3, 62). Fifth, the economic feasibility of detoxification technologies requires greater consideration. Reported toxin-reduction efficiencies alone do not establish practical suitability because treatment costs, energy and reagent requirements, processing losses, nutritional quality, equipment requirements, scalability and waste management can substantially influence the overall cost-effectiveness of a treatment (80, 96). Comparative technoeconomic assessments are therefore needed to identify detoxification approaches that provide an appropriate balance between toxin reduction, product quality, safety and processing cost. Finally, mycotoxin contamination has important implications for international trade because failure to meet regulatory maximum limits can result in increased testing, rejection of consignments, recalls and economic penalties. Harmonisation of regulatory standards and improved surveillance are therefore important for reducing trade barriers and protecting the competitiveness of oilseed-producing countries (72, 74, 75).

Nanotechnology-assisted detoxification and smart packaging approaches are also potential research directions. Nano-adsorbents, photocatalytic nanomaterials and active antifungal packaging systems may increase toxin adsorption efficiency and inhibit fungal growth under storage conditions. In addition, integrated nano-biosensing platforms can act as detection and detoxification of toxin systems at the same time, providing an integrated approach. However, toxicological safety, environmental risks and regulatory standardisation are considerable challenges that merit further analysis before they can be taken up at large scale (5, 88, 90). Furthermore, omics-based designs should be further investigated in future studies to understand the pathogenicity of fungi, toxin biosynthesis pathways and host–pathogen interactions in oilseed systems. Such molecular-level knowledge may promote the emergence of resistant cultivars, biomarker-based surveillance systems and interventions against mycotoxigenic fungi (97, 98). The application of artificial intelligence (AI), machine learning (ML) and big data analytics in mycotoxin surveillance systems would also be of enormous potential. Predictive models involving climate parameters, fungal population status, the storage environment and historical contamination data have the potential to enhance predictions of contamination and, consequently, to be used to inform accurate risk management procedures at the regional and farm levels (4, 60, 99). Finally, promoting a global regulatory framework, improving farmers' perceptions and interdisciplinary research will be essential to improve the management risk of mycotoxins for oilseed systems. Improved training programs for farmers after harvest, more efficient analytical infrastructure and the synchronisation of international standards for food

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safety will also encourage safer oilseed farming and reducing economic losses and public health risk (3, 72, 74, 100).

Despite substantial progress in understanding mycotoxin contamination in oilseed systems, several important research gaps remain. First, the true extent of contamination by multiple mycotoxins in oilseeds and oilseed-derived products remains insufficiently characterised. Most studies have focused on individual mycotoxins, whereas the simultaneous occurrence of multiple toxins may better represent real-world contamination and may complicate risk assessment. Future surveillance should therefore employ validated multi-mycotoxin analytical methods to determine the prevalence, concentration ranges and co-occurrence patterns of major mycotoxins across different oilseed commodities and geographical regions (101, 102). Recent evidence indicates that climate-related changes may also modify fungal interactions and consequently influence the prevalence and co-occurrence of mycotoxins, further emphasising the need for multi-mycotoxin surveillance (101). Second, the differential response of toxigenic and nontoxigenic fungal strains to climate change remains an important unresolved question. Increasing temperature, drought stress, altered relative humidity and other climate-related stresses may affect fungal growth, competition, host susceptibility and mycotoxin biosynthesis; however, these responses can vary among fungal species and strains. In particular, the extent to which climate change will alter the competitive balance between toxigenic and non-toxigenic populations of *Aspergillus* and other mycotoxigenic fungi remains insufficiently understood. Future studies should integrate strain-level characterisation with climate projections and ecological modelling to develop region-specific predictions of changes in toxigenic fungal populations and mycotoxin risk (101). Third, the limited large-scale adoption of biological control technologies despite promising laboratory and field results represents an important translational research gap. The effectiveness demonstrated under controlled conditions does not always translate directly into widespread adoption because performance can be influenced by agroecological variability, competition with indigenous fungal populations, formulation stability, application timing, production capacity, cost, farmer acceptance, regulatory requirements and scalability. Recent experience with atoxigenic *A. flavus* based biocontrol has demonstrated that industrial-scale manufacturing, formulation, commercialisation strategies, incentives and partnerships are important for translating biological efficacy into wider practical use (103). Future research should therefore move beyond proof-of-concept studies towards multilocation field validation, formulation and shelf-life optimisation, cost-effectiveness assessment, regulatory evaluation and long-term ecological safety (103). Despite the advances discussed above, several unresolved challenges require focused attention to strengthen sustainable mycotoxin management in oilseed systems. Omics-based approaches should be further developed for the surveillance of fungal populations, identification of toxigenic traits, characterisation of toxin-biosynthesis pathways and discovery of biomarkers for early risk prediction (97, 98). Multiple mycotoxin surveillance and risk assessment methods are also needed because simultaneous exposure to different mycotoxins may not be adequately represented by assessments based on individual toxins alone. Biological control strategies require further field-scale validation to determine the stability, efficacy, formulation performance and consistency of selected nontoxigenic microorganisms under diverse environmental and production conditions (89, 96). Similarly, nanotechnology-based detoxification requires standardised evaluation of nanoparticle toxicity, migration, environmental persistence, recovery and food-matrix interactions before wider commercial application (94–96). Finally, greater harmonisation of international regulatory limits, analytical methods, validation procedures and safety criteria is needed to facilitate consistent risk assessment, regulatory compliance and safe international trade of oilseed commodities (72, 74, 78, 100).

4. Conclusion

Mycotoxigenic fungi are important contaminants of oilseeds and can compromise food safety, quality and economic value. *Aspergillus*, *Fusarium*, *Penicillium* and *Alternaria* are among the major genera associated with mycotoxin contamination in oilseed systems, with aflatoxins remaining a major concern, particularly in groundnut and other susceptible oilseed commodities. Mycotoxin occurrence is influenced by fungal ecology, temperature, water activity, crop stress and postharvest storage conditions. Conventional processing can reduce mycotoxin levels but may not achieve complete detoxification and may have limitations related to product quality and toxin transformation. Advanced analytical approaches, including chromatographic and mass-spectrometric techniques, provide sensitive and reliable detection, while emerging biosensors offer potential for rapid field screening. Biological control using selected nontoxigenic microorganisms represents a promising and environmentally sustainable strategy for reducing fungal colonisation and toxin accumulation. However, challenges related to efficacy, safety, scalability, cost, regulatory acceptance and field validation remain. Future management should integrate improved surveillance, climate-based risk prediction, rapid detection, biological control, safe processing and appropriate regulatory frameworks. Overall, an integrated and sustainable approach across the entire oilseed value chain is essential to reduce mycotoxin risk and protect food safety, public health and the economic value of oilseed commodities.

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Authors' contributions

YN performed literature collection and prepared the original manuscript. PV and HS conducted supervision, formal analysis, conceptualisation and validation of the manuscript. EA assisted in language editing and alignment of manuscript. JC contributed to conceptualisation. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly in order to improve language and readability, with caution. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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