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Titled

Advanced strategies for mycotoxin detection and biocontrol in food and feed system.

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Dedication

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Abstract

Mycotoxins are toxic secondary metabolites produced by specific fungal species that pose significant risks to human and animal health and cause substantial economic losses in the agri-food industry. This review provides a comprehensive overview of current strategies for the detection and prevention of mycotoxins in food and feed. Traditional laboratory techniques, such as high-performance liquid chromatography (HPLC), gas chromatography (GC), liquid chromatography-tandem mass spectrometry (LC-MS/MS), and enzyme-linked immune sorbentassays (ELISA), remain widely used for accurate mycotoxin quantification. In parallel, emerging technologies such as biosensors, fluorescence spectroscopy, hyperspectral imaging, and nanotechnology-based assays are gaining attention for their potential in rapid and on-site detection. Recent advancements also highlight the integration of artificial intelligence (AI), including machine learning algorithms and computer vision systems, to enhance the accuracy, speed, and automation of detection processes, particularly in image-based and spectral analysis. In terms of prevention, the study emphasizes good agricultural practices, post-harvest management, physical and chemical detoxification techniques, and regulatory measures implemented to mitigate mycotoxin contamination. By combining traditional expertise with innovative technologies, including AI, this work aims to support the advancement of food safety systems and the protection of public health.

Keywords : mycotoxins, detection techniques, biosensors, artificial intelligence, preventive strategies, food safety.

Résumé

Les mycotoxines sont des métabolites secondaires toxiques produits par certaines espèces fongiques, représentant un risque important pour la santé humaine et animale, ainsi qu'une source de pertes économiques considérables dans le secteur agroalimentaire. Cette revue présente un aperçu approfondi des stratégies actuelles de détection et de prévention des mycotoxines dans les denrées alimentaires et les aliments pour animaux. Les techniques de laboratoire traditionnelles, telles que la chromatographie liquide à haute performance (HPLC), la chromatographie en phase gazeuse (GC), la chromatographie liquide couplée à la spectrométrie de masse en tandem (LC-MS/MS) et les dosages immuno-enzymatiques (ELISA), restent largement utilisées pour une quantification précise des mycotoxines. Parallèlement, les technologies émergentes — telles que les biosenseurs, la spectroscopie de fluorescence, l'imagerie hyperspectrale et les tests basés sur les nanotechnologies suscitent un intérêt croissant pour leur potentiel de détection rapide et sur site. Les avancées récentes mettent également en évidence l'intégration de l'intelligence artificielle (IA), notamment les algorithmes d'apprentissage automatique et les systèmes de vision par ordinateur, afin d'améliorer la précision, la rapidité et l'automatisation des processus de détection, en particulier dans les analyses d'images et spectrales. En matière de prévention, l'étude souligne l'importance des bonnes pratiques agricoles, de la gestion post-récolte, des méthodes de détoxification physiques et chimiques, ainsi que des cadres réglementaires mis en place pour limiter la contamination. En alliant les approches classiques aux technologies innovantes, y compris l'IA, ce travail vise à contribuer au renforcement de la sécurité alimentaire et à la protection de la santé publique.

Mots-clés : mycotoxines, techniques de détection, biosenseurs, intelligence artificielle, stratégies préventives, sécurité alimentaire.

الملخص

الميكوتوكسينات هي نواتج أيضية ثانوية سامة تنتجها أنواع معينة من الفطريات، وتمثل مخاطر كبيرة على صحة الإنسان والحيوان، كما تسبب خسائر اقتصادية كبيرة في قطاع الصناعات الزراعية والغذائية. تقدم هذه المراجعة نظرة شاملة على الاستراتيجيات الحالية للكشف عن الميكوتوكسينات والوقاية منها في الأغذية والأعلاف. لا تزال التقنيات المخبرية التقليدية، مثل الكروماتوغرافيا السائلة عالية الأداء(HPLC) ، والكروماتوغرافيا الغازية(GC) ، والكروماتوغرافيا السائلة المقترنة بمطياف الكتلة المزدوج(LC–MS/MS) ، والاختبارات المناعية المرتبطة بالإنزيمات(ELISA) ، مستخدمة على نطاق واسع لقياس الميكوتوكسينات بدقة. في الوقت نفسه، تكتسب التقنيات الحديثة، مثل المستشعرات الحيوية، ومطيافية التألق، والتصوير فائق الطيف، والاختبارات المعتمدة على تقنيات النانو، اهتمامًا متزايدًا لقدرتها على الكشف السريع والموقعي. كما تسلط التطورات الحديثة الضوء على دمج الذكاء الاصطناعي، بما في ذلك خوارزميات التعلم الآلي وأنظمة الرؤية الحاسوبية، لتحسين دقة وسرعة وأتمتة عمليات الكشف، وخاصة في تحليل الصور والطيف. وفي مجال الوقاية، تؤكد الدراسة على أهمية الممارسات الزراعية الجيدة، وإدارة ما بعد الحصاد، وتقنيات إزالة السمية الفيزيائية والكيميائية، والإجراءات التنظيمية التي تهدف إلى الحد من تلوث الميكوتوكسينات. من خلال الجمع بين الخبرات التقليدية والتقنيات المبتكرة، بما في ذلك الذكاء الاصطناعي، يهدف هذا العمل إلى دعم تطوير أنظمة سلامة الغذاء وحماية الصحة العامة.

الكلمات المفتاحية :الميكوتوكسينات، تقنيات الكشف، المستشعرات الحيوية، الذكاء الاصطناعي، استراتيجيات الوقاية، سلامة الغذاء .

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Liste of abbreviations

3-ADON: 3-acetyldeoxynivalenone

3-NPA: 3-nitropropionic

AF: Aflatoxin

AI : Artificial intelligence

AIE : Aggregation-induced emission

ANNs : Artificial neural networks

AOH: Alternariol

Apt : Aptamer

ATA: Alimentary toxicaleukia

AuNPs: Gold nanoparticles

BFH12 : Bovine fetal hepatocyte cell line

CAP : Cold Atmospheric Plasma

CEN : European Committee for Standardization

CNN : Convolutional neural networks

CNPs : Carbon-based nanoparticles

COL18A1: Collagen sort XVIII alpha 1 chain

COL1A2 : Collagen sort 1 alpha 2 chain

CTN : Citrinin

CV : Cyclic voltammetry

CYP : P450 cytochromes

DAS : Diacetoxyscirpenol

DL : Deep learning

DON: Deoxynivalenol

DPV : Differential pulse voltammetry

EAs : Ergot alkaloids

EC : Electrochemical

EC : European Commission

EIS : Electrochemical impedance spectroscopy

ELISA : Enzyme-linked immunosorbent assay

ENN : Enniatin

FAO : Nourishment and Horticulture Organization

FB1 : Fumonisins

FDA : US Nourishment and Medicate Organization

FICH : Fluorescence in situ hybridization

FTIR : Fourier-transform infrared spectroscopy

GC : Guanine–Cytosine

GNPs : Gold nanoparticles

GST : Glutathione-S-transferase

HIS : Hyperspectral imaging

HPLC : High performance liquid chromatography

HPP : High-pressure processing

IARC : Universal Office for Inquire about on Cancer

JECFA: Joint Master Committee on Nourishment Added substances

KBD : Kashin–Beck illness

LAB : Lactic acid bacteria

LAMP: Loop-mediated isothermal amplification

LC : Liquid chromatography

LC-MS : Liquid chromatography –mass spectrometry

LFD : Lateral flow device

LMH : Hepatocarcinoma cell line

LOD : Limit of detection

LOQs : Limits of quantification

MALDI-TOF MS: Matrix-assisted laser desorption/ionization time-of-flight Mass spectrometry.

MIP : Molecularly Imprinted polymers

ML : Machine Leargning

NEOs : Natural Essential oils

NIV : Nivalenol

NMR: Nuclear magnetic resonance

OTA : Ochratoxin

OWLS: Optical waveguide lightmode spectroscopy

PAT : Patulin

PBS : phosphate-buffered saline

PBS : phosphate-buffered saline

PCR : Polymerase chain reaction

PDA : Photodiode array

PEFs : Pulsed electric fields

QCM : Quartz crystal microbalance

QqQ : Triple quadrupole

ROS : Receptive oxygen species

SPR : Surface plasmon resonance

SWV : Square wave voltammetry

TA : Thymine–Adenine

TLC : Thin –layer chromatograpy

TLR2 : Toll-Like Receptor

TOF : Time-of-flight

UV : Ultra violet-visible

WMTs : Microwave-based thermal treatments

ZEA : Zearalenone/F-2Toxin

ZEL: Zearalenol

ZEN : Zearalenone

Introduction

Mycotoxins are toxic secondary metabolites produced by filamentous fungi such as *Aspergillus*, *Fusarium,* and *Penicillium*. These compounds can cause severe illnesses in both humans and animals **(Umereweneza *et al.*,2018)**. Fungal contamination of food and feed by mycotoxin-producing species results in significant socio-economic losses and health concerns **(Abd-Elghany *et al.*, 2015 ;Montanari *et al.*, 2016)**. Globally, mycotoxins pose a serious threat to food safety, affecting a wide range of agricultural products, including cereals (corn, rice, wheat, barley), legumes, fruits, nuts (e.g., peanuts, almonds, walnuts, pistachios), coffee, cottonseed, spices (such as pepper, paprika, and ginger), and meat **(Darwish *et al.*, 2014; Pleadin *et al.*, 2019)**. According to (**Mesterhazy *et al.*, 2020)**, approximately 1.3 billion metric tons of food, equivalent to nearly one-third of global production, are lost each year due to mycotoxin contamination.

Currently, about 400 different mycotoxins have been identified, although only approximately 30 are known to pose significant health risks to humans and animals **(Donat *et al.*, 2018; Umereweneza *et al.*, 2018)**. The most recognized toxic mycotoxins include aflatoxins (AFs), ochratoxin A (OTA), *Alternaria*toxins (alternariol (AOH), alternariolmonomethylether (AME), tentoxin (TEN), altenuene (ALT), fumonisins (FMNs), trichothecenes (T-2/HT-2 toxins), deoxynivalenol (DON), nivalenol (NIV), citrinin (CIT), zearalenone (ZEN), ergot alkaloids, and patulin (PAT). Among these, aflatoxins are especially hazardous due to their high toxicity and classification as Group 1 human carcinogens by the International Agency for Research on Cancer (IARC) **(Anfossi *et al.*, 2016; Shephard *et al.*, 2008)**.

Beyond their carcinogenic potential, mycotoxins can induce allergies, organ toxicity, and various other health issues **(Alshannaq *et al.*, 2017)**. The effects depend on exposure levels and include liver cancer and immune suppression (AFB1, OTA), abdominal discomfort (DON), hormonal disruption (ZEN), inhibited growth (T-2 toxin), and DNA damage **(Amuzie *et al.*, 2010; Rasic *et al.*, 2019)**. Prolonged exposure to multiple mycotoxins can result in synergistic toxicological effects **(Sun *et al.*, 2015; Zhou *et al.*, 2017)**. Therefore, accurate detection of mycotoxinsis vital for food safety and public health.

Analytical techniques such as gas chromatography (GC), high-performance liquid chromatography (HPLC), and liquid chromatography-mass spectrometry (LC-MS) are commonly used to identify mycotoxins. However, due to their complexity and cost, these

methods are often impractical for routine food testing, especially in developing regions **(Marc,2019 ; Awuchi *et al.*, 2021)**. To address these challenges, newer and more accessible detection technologies have emerged, including enzyme-linked immunosorbent assays (ELISA), lateral flow assays (LFAs), and biosensors. These tool enable rapid detection and quantification of mycotoxins.

In recent years, artificial intelligence (AI) has also emerged as a powerful tool in the detection and risk assessment of mycotoxins. Machine learning algorithms and deep learning models have been developed to process large datasets, identify patterns in spectroscopic or chromatographic outputs, and predict contamination levels with high accuracy. AI-based platforms enhance detection sensitivity, reduce human error, and facilitate real-time decision-making in food safety monitoring systems (**Chakraborty *et al.*, 2024 ; Sarker *et al.*, 2021; Zhang *et al.*, 2020).**

Furthermore, AI integration with image analysis, hyperspectral imaging, and sensor technologies holds great promise for non-invasive, high-through put mycotoxin screening in various food matrices **(Mishra *et al.*, 2021)**.

In parallel, strategies aimed at detoxifying or eliminating mycotoxins from food are under active investigation. Physical, chemical, and biological methods are typically employed for this purpose. Efforts to control fungal proliferation and minimize mycotoxin contamination in various food products have traditionally relied on these approaches. However, conventional methods often alter the sensory and nutritional characteristics of food, such as flavor, texture, and composition, as highlighted by recent studies **(Zhang *et al.*, 2019)**. Additionally, certain mycotoxins exhibit high thermal stability, rendering them resistant to degradation during standard food processing techniques like heating **(Peng *et al.*, 2018)**.

Consequently, there is growing interest in alternative, non-thermal approaches that reduce mycotoxins levels without compromising food quality. It is essential to investigate these innovative strategies thoroughly to enhance their efficiency in mitigating mycotoxin contamination and reinforce food safety.

This research provides an extensive review of the current scientific literature concerning the toxicological impact of mycotoxins and outlines the latest advancements in detection techniques across diverse food matrices. Moreover, it examines the practical implications and effectiveness of novel preventive technologies, including cold atmospheric plasma (CAP), the application of polyphenols and flavonoids, the use of magnetic materials and nanoparticles, the incorporation

of natural essential oils (NEOs), and the integration of artificial intelligence-based approaches for predictive modeling and detection.

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Bibliographic Synthesis

I. Overview of molds and mycotoxins

I.1. Molds

Molds are filamentous fungi belonging to the kingdom *Fungi*, characterized by their ability to grow as multicellular structures composed of hyphae. These fungi play essential roles in natural ecosystems by decomposing organic matter, recycling nutrients, and forming symbiotic relationships with plants. However, they can also cause food spoilage and produce mycotoxins harmful to human health. Some molds, such as *Penicillium* and *Aspergillus*, are utilized in the food and pharmaceutical industries for antibiotic production, fermentation, and the development of cheeses and soy products. Others, like *Stachybotrys*, are known for their toxic effects on indoor air quality (**Hocking, 2009)**.

I.2. Vegetative structure of molds

The basic structural unit of molds is the hypha, which collectively forms a network known as mycelium. Hyphae can be septate (divided by cross-walls) or coenocytic (lacking septa), facilitating cytoplasmic streaming and nutrient transport. The mycelium serves multiple functions, including nutrient absorption, growth, and reproduction. Some molds also produce specialized structures, such as conidiophores and sporangia **(Figure1,2,3)**, represent microscopic aspect of *Aspergillus*, *Penicilluim* and *Fusarium* respectively, which aid in spore formation and dispersal. Additionally, certain molds develop rhizoids for anchorage and haustoria for parasitic interactions with host cells (**Alexopoulos *et al*., 1996**).

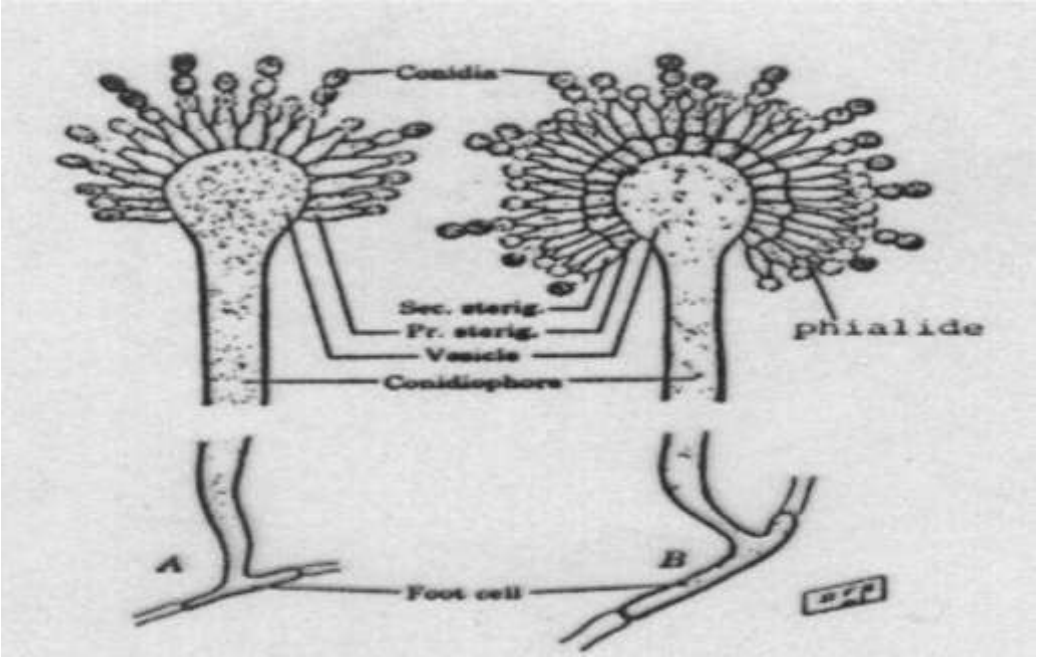

Figure 1 : Aspect microscopic *Aspergillus* (Barnett & Hunter,1972)

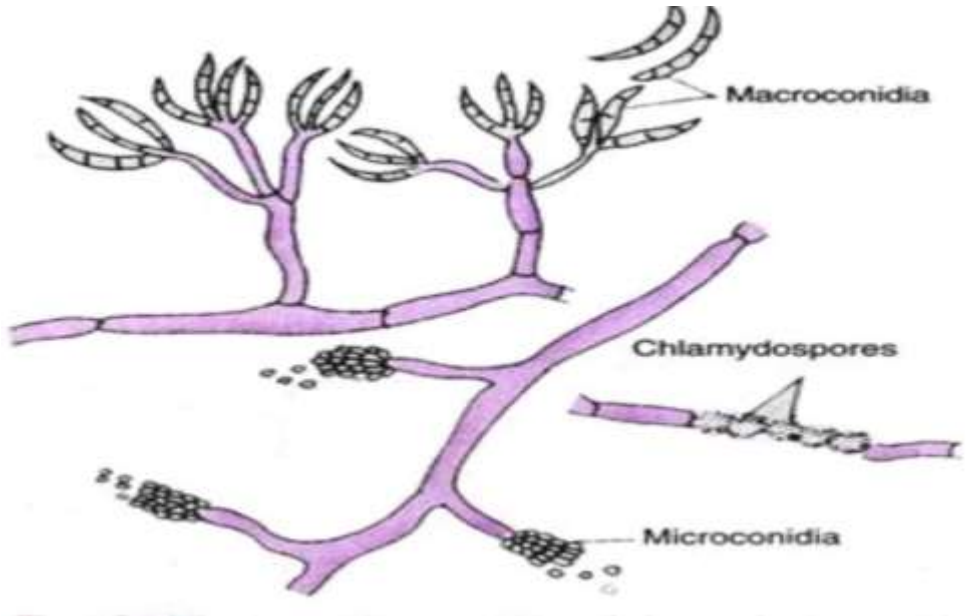

Figure 2 : Microscopic Aspect of *Penicillium* **(Tabuc, 2007).**

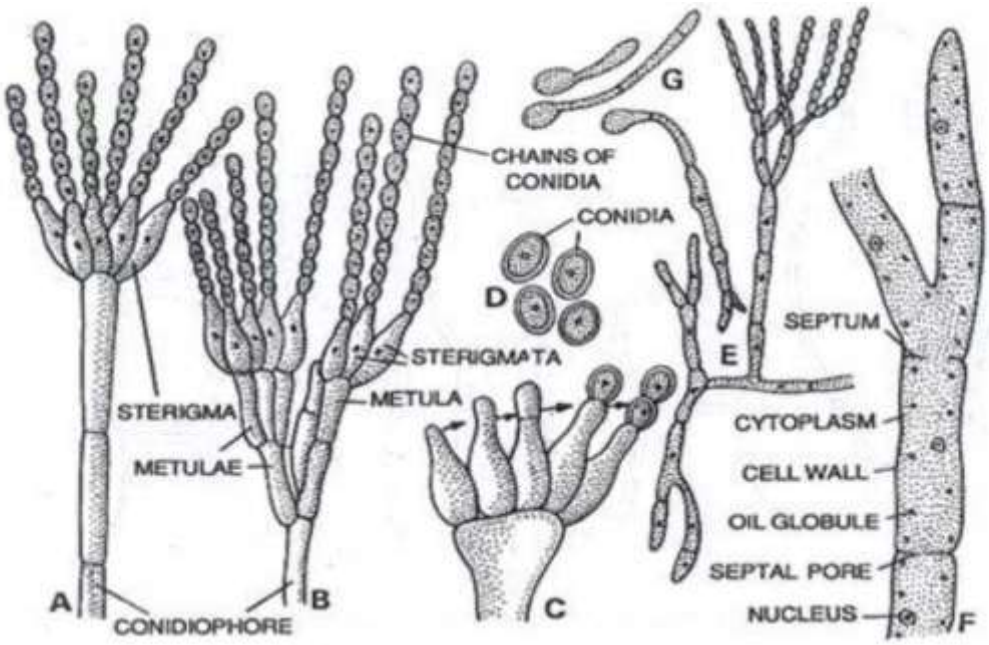

Figure 3 : microscopic Aspect of *Fusarium*

I.3. Physiological characteristics

Molds exhibit unique physiological traits that allow them to thrive in diverse environments. They are heterotrophic organisms that obtain nutrients by secreting extracellular enzymes such as cellulases, proteases, and amylases to break down organic matter into absorbable molecules. Molds can grow in a wide range of temperatures, with optimal growth occurring between 20–30°C, although thermophilic molds can survive at higher temperatures. They also tolerate varying pH levels and high humidity, making them resilient in different ecological niches. Some species produce secondary metabolites, including antibiotics (e.g., penicillin from *Penicillium*) and mycotoxins (e.g., aflatoxins from *Aspergillus flavus*), which have significant health and industrial implications (**Carlile *et al*., 2001).**

I.4. Growth of molds

Mold growth depends on environmental factors such as moisture, temperature, nutrient availability, and oxygen levels. The life cycle of molds typically begins with spore germination, followed by hyphal elongation and mycelium expansion Figure4 represent Cycle reproduction sexuée and asexuée of Ascomycètes. Under favorable conditions, molds rapidly colonize organic

substrates, forming visible fungal colonies. In food products, mold growth results in spoilage, discoloration, and potential toxin production, posing health hazards. Some molds, such as *Botrytis cinerea*, cause plant diseases, while others form beneficial associations with plants, such as mycorrhizal fungi. Molds are also known for their ability to degrade synthetic materials, including plastics and paints, due to their potentenzymatic activity (**Hocking & Pitt ,2009**).

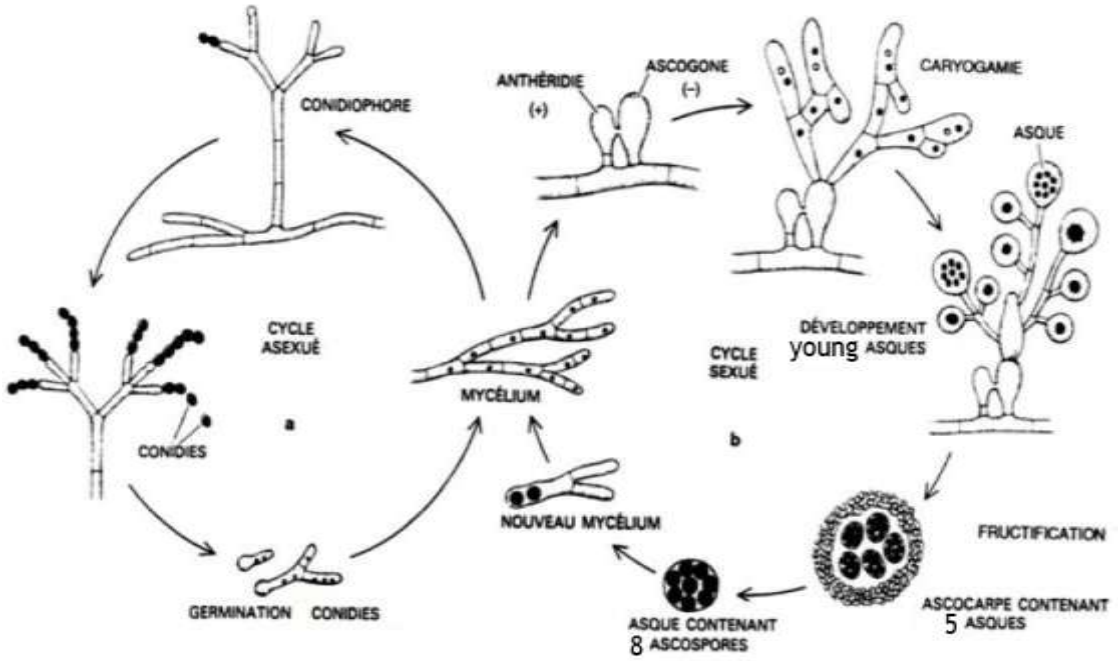

Figure 4. Cycle reproduction sexuéeand asexuée of Ascomycètes **(Meyer,2004)**

I.5. Classification of molds

Molds are classified based on their morphological characteristics, reproductive structures, and genetic traits. The main taxonomic groups include:

- **Zygomycota:** Fast-growing molds with non-septate hyphae, such as *Rhizopus* species, which are commonly found in soil and decaying organic matter. These molds reproduce sexually via zygospores and asexually via sporangiospores.
- **Ascomycota:** Septate molds that produce spores in sac-like structures called asci, including *Penicillium* and *Aspergillus*. These fungi are economically important in biotechnology and food industries.
- **Basidiomycota:** Some molds within this group form complex fruiting bodies, such as *Cryptococcus*, a pathogenic yeast form fungus that affects humans.

- **Deuteromycota (Fungi Imperfecti):** Molds with no known sexual reproduction stage, often grouped based on asexual spore production. Many species in this group, such as *Fusarium* and *Alternaria*, are plant pathogens and toxin producers **(Kirk *et al*., 2008).**

I .6. Mycotoxins

I.6.1. Definition of Mycotoxins

Mycotoxins are toxic secondary metabolites produced by molds, primarily from the gener *Aspergillus*, *Penicillium*, and *Fusarium*. These compounds are generated during the secondary .metabolic processes of fungi and can contaminate crops both in the field and during storage

They are naturally occurring contaminants found in a wide range of plant-based products, particularly cereals, as well as fruits, nuts, seeds, almonds, forage, and processed foods derived .from these raw materials, posing risks to both human and animal health

Mycotoxins are small, water-insoluble molecules that are highly resistant to biological) degradation and can withstand high temperatures vC. Consequently, they often °250 up to remain in food products even after cooking, sterilization, or exposure to extreme pH conditions. These toxins can persist much longer in food than the molds that initially produced them (**Guezlane-Tebibel *et al*., 2016).**

I.6.2.Major mycotoxins and their sources

Although numerous fungal toxins exist only a limited number are considered significant threats to food safety **(Halasz *et al*.,2009).** The most agriculturally important and concerning mycotoxins include aflatoxins, ochratoxins, fumonisins , trichothecenes , zearalenone , and other classes such as ergot alkaloids and patulin **Figure 5 (Abrunhosa *et al* ., 2016) .**

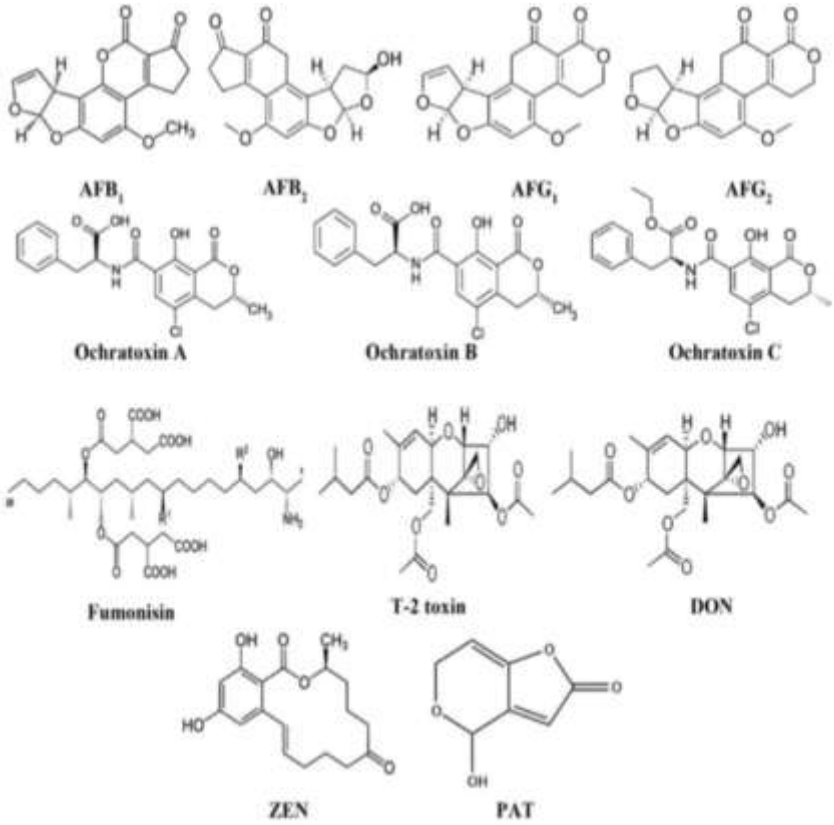

Figure 5 : Chemical structures of important representative mycotoxins **(Streit *et al*., 2013).**

I.6.2.1. Aflatoxins (AFTs)

Aflatoxins (AFs) have a place to a course of difurano coumarins characterized by a bifuran gather connected to the coumarin core and either a pentanone ring or a lactone ring (**Schuda *et al.*, 1980**). AFTs include around 20 basically closely related compounds delivered by different *Aspergillus* species, such as *A. flavus*, *A. parasiticus*, and, seldom, *A. nomius (***Janik *et al.*, 2020).** Among the foremost critical AFTs are those having a place to arrangement B and G, particularly aflatoxins B1 (AFB1) and B2 (AFB2), which are primarily created by *A. flavus* and aflatoxins G1 and G2, commonly found in *A. parasiticus* **Figure4 (Kumar *et al.*, 2017**). AFB1 is considered the foremost common nourishment contaminant conjointly the foremost harmful AFs **(Cao *et al*., 2022).** Another eminent part is AFM1, an AFB1 subsidiary excreted within the drain of dairy animals and other ruminants that have devoured AFB1-contaminated bolster (**Abrunhosa *et al.*, 2016**). Due to a solid connect between their utilization and cancer event, AFTs are authoritatively recognized as human carcinogens, and their levels are entirely

controlled in numerous nations (**Rushing *et al*., 2019**). AFTs basically influence the liver, with a few thinks about connecting liver cancer to the nearness of AFTs in nourishment **(Liu et *al* .,2010; Magnussen *et al.,* 2013; Wild *et al.,* 2009**)**.** It is accepted that the components of AFs induced carcinogenesis include tumor advancement and movement, at the side actuating different chromosomal variations, uncontrolled DNA union, and chromosomal strand breaks in human cells (**Magnussen *et al.,* 2013)**. AFTs are fundamentally experienced in cereals, rice, and corn, in spite of the fact that they can to be recognized in soybeans, sorghum, pistachio nuts, dried natural product, lager, drain, and flavors (**Mahato *et al.,* 2019**).

I.6.2.2. Zearalenone (ZEN)

Zearalenone, too known as F-2 poison Figure5, may be a phenolic resorcylic corrosive lactone biosynthesized in a assortment of soil parasites of the *Fusarium* family, counting *F.graminearum, F. culmorum, F. cerealis, F. equiseti, F. crookwellense, and F. semitectum* **(Janik *et al.,* 2020**). ZEN is basically found in mold-infested nourishment and crops, with a overwhelming nearness in grains, such as corn, wheat, rice, grain, sorghum, soybeans, oats, and related items (**Han *et al.,* 2022**). Defilement of creature drain can happen when their bolster contains raised levels of ZEN **(Prelusky *et al*., 1990).** ZEN is quickly retained through the gastrointestinal tract after verbal introduction and shows a wide run of destructive bioactivities, such as hepatotoxicity (**Marin *et al.,* 2019; Karaman *et al.,* 2020**), immunotoxicity **(Hueza *et al*., 2014; Islam *et al*., 2017**) and carcinogenicity (**Ahamed *et al.,* 2001; Cai *et al*., 2019).** In any case, the foremost prominent and commonplace impact of ZEN is its estrogenic movement. In conjunction with its analogs, ZEN applies a critical impact on estrogen receptors, conceivably due to its structure taking after that of endogenous estrogen (**Janik *et al* ., 2020**). It has been appeared that ZEN and its subsidiaries affect the amalgamation and discharge of a few steroid sex hormones, counting testosterone, estradiol, and progesterone, through a arrangement of instruments, such as influencing the exercises of cellular mitochondria and steroidogenic chemicals (**Zheng *et al*., 2019**). ZEN altogether impacts the regenerative frameworks of animals and creatures (**Dellafiora *et al*., 2020**). These impacts incorporate diminished richness, untimely adolescence, changes in thyroid, adrenal, and pituitary organ morphology, and changes in serum progesterone and estradiol levels (**Zinedine *et al*., 2007**).

I.6.2 .3. Ochratoxins (OTs)

Ochratoxins are polyketides determined from dihyrdocoumarins created by a few parasitic species, counting *A. ochraceus, A. carbonarius, A. niger, P. verrucosum, P. nordicum, and P.*

viridicatum (**Reddy *et al*., 2010; Janik *et al*., 2020**). Ochratoxin A (OTA) is the foremost common and poisonous among OTs, which moreover incorporate ochratoxin B (OTB) and ochratoxin C (OTC) (**Figure 4)** (**Janik *et al*., 2020**). This poison basically targets the kidney and is suspected as a potential causal calculate in certain kidney infections, urothelial tumors, and inveterate interstitial nephropathy **(Bui-Klimke *et al*., 2015)**. Moreover, OTA is related with mutagenic, teratogenic, neurotoxic, hepatotoxic, and immunotoxic impacts (**Clark *et al* ., 2006; Reddy *et al*., 2010**). It is commonly found in wheat, rye, coffee beans, nuts, raisins, wine, and pork and its determined items. Due to its predominance in different commodities and its moderate disposal from the body, OTA has been recognized within the blood, breast drain, and pee, both in its unique and metabolized states (**Bui-Klimke *et al*.,2015; Abrunhosa *et al*.,2016**).

I.6.2.4. Fumonisins (FB)

Fumonisins include an stretched hydrocarbon chain connected to a few methyl and hydroxyl bunches, alongside one free amino and two tricarballylate functionalities, which are primarily dependable for their harmfulness **(Qu *et al*.,2022; Vanhoutte *et al.*,2016**). FUMs are overwhelmingly delivered by Fusarium parasitic species, such as *F. verticillioides* and *F.proliferatum* (**Qu *et al*.,2022**); in any case, *A. niger* can moreover synthesize certain FUMs (**Frisvad *et al*.,2007).** There are at slightest 28 distinguished FBs categorized into four bunches (A, B, C, and P) based on auxiliary likenesses (**Abrunhosa *et al*., 2016; Qu *et al*., 2022).**

With respect to nourishment security, B arrangement FBs are of noteworthiness due to their visit discovery. Inside this bunch, FB1 and FB2 are particularly essential (**Waśkiewicz *et al*., 2012; Qu *et al*., 2022**). FBs initiate a wide extend of antagonistic impacts in life forms, such as autophagy, apoptosis, neurotoxicity, immunotoxicity, regenerative harmfulness, and carcinogenicity (**Voss *et al*., 2013**). The essential component through which FBs show their poisonous quality is by restraining ceramide synthase, subsequently disturbing sphingolipid biosynthesis and affecting cellular development, separation, and morphology (**Voss *et al*., 2007**).

I.6.2.5. Trichothecenes

Trichothecenes speak to a assorted bunch of over 200 chemically related compounds delivered by diverse filamentous parasitic species, such as *Fusarium, Myrothecium, Trichoderma,* and *Trichothecium* (**McCormick *et al.*, 2011; Janik *et al.*, 2021**). They share a center structure of 12,13-epoxytrichothec-9-ene and are categorized into four sorts, A, B, C, and D, based on the substitution of the center skeleton (**Ueno *et al*., 1984**). Essential concern for

nourishment security are sort *A* and *B trichothecenes*, transcendently created by *Fusarium* species. Sort *A trichothecenes* incorporate T-2 poison, which is respected as the foremost considered and most harmful among all trichothecenes **(Li *et al*.,2011; Janik *et al*., 2021**), along with HT-2 poison and diacetoxyscirpenol (DAS) . Sort B trichothecenes encompass deoxynivalenol (Wear) and nivalenol (NIV) (**Abrunhosa *et al*., 2016;Ueno *et al*., 1984**). Wear, too known as vomitoxin, is additionally a well-studied mycotoxin due to its far-reaching event in foodstuffs like cereal-based merchandise (**Sobrova *et al*., 2010**); in any case, it is considered one of the slightest harmful trichothecenes. The nearness of Wear is frequently respected as an marker of other, more harmful trichothecenes and mycotoxins **(Sobrova *et al*., 2010**). A eminent characteristic of Wear is its warm steadiness, permitting it to resist tall temperatures for an expanded period (**Vidal *et al*., 2015**).

Trichothecenes are basically found in cereals, such as wheat, rye, oats, and cor **(Pascari *et al*., 2020).** Their tall level of cytotoxicity is communicated by their capacity to cause oxidative cell harm, restrain nucleic corrosive and protein amalgamation, meddled with cell division and mitochondrial operations, and compromise the solidness of cell films (**Ueno *et al*., 1977; Janik *et al*., 2021**). The characteristic epoxide ring in their chemical structure is accepted to be an essential supporter to their poisonous impacts **(Janik *et al*., 2021**). Like other mycotoxins, trichothecenes cause a cascade of wellbeing impacts, such as hepatotoxicity, nephrotoxicity, neurotoxicity, immunotoxicity, and regenerative poisonous quality (**Ihara *et al*., 1997; Yang *et al*., 2018; Zhang *et al*., 2018 ;Nayakwadi *et al*., 2020**).

I.6.2.6 Patulin (PAT)

Patulin is another common mycotoxin conveyed by different people of the parasitic genera *Penicillium*, *Aspergillus*, and *Byssochlamys*, overwhelm mingly by *P. expansum* (**Rice *et al*., 1977; Lončarić *et al*., 2021)**. Chemically, PAT can be a small polyketide with a cyclic γ-lactone Figure 5, it is water-soluble and highlights a moo nuclear weight **(Puel *et al*., 2010**). PAT is commonly found in common items and vegetables, especially in apples and apple things, as well as in other normal items, such as pears, cherries, grapes, and their things (**Lončarić et *al*., 2021; Wei *et al*., 2022**). PAT can activate genotoxicity, immunotoxicity, and neurotoxicity in animals (**Alves *et al*., 2000; Moake *et al*., 2005**). The hurtfulness is acknowledged to result from obstacles of PAT with thiol-containing cellular components and amino acids inside the plasma film (**Fliege *et al*., 1999; Alves *et al*., 2000**), unavoidably driving to prevention of protein and

DNA amalgamations and unsettling influence of interpretation and elucidation (**Wei *et al.*, 2022**).

I.6.2.7. T-2 Toxin

T-2 poison is one of the foremost poisonous mycotoxins, basically delivered by *F. sporotrichoides, F. poae, F. acuminatum*, and *F. equiseti*, which are primarily found in locales with cold climate and damp capacity conditions (**Kang *et al.*, 2020;Ling *et al.*, 2020**). The World Wellbeing Organization categorized T-2 poison as an unavoidable contaminant in rural items, human nourishment, and creature nourish as early as in 1973. T-2 poison actually happens in cereals, particularly in wheat, oats, grain, conjointly in cereal-based items. It makes this poison destructive to human and creature wellbeing (**Sun *et al.*, 2020**). Defilement of overwintered wheat caused an outbreak of alimentary toxicaleukia (ATA) within the 1930s within the previous Soviet Union and was related with other gastrointestinal issues (**McCormick *et al.*, 2012**). The etiology of Kashin–Beck illness (KBD) is still vague, but it can be suspected that T-2 mycotoxin is the cause of this infection. In Chinese towns, which are endemic for KBD, the nearness of T-2 poison is moderately tall with an normal extend of 78.91 μg/kg in wheat and 47.47 μg/kg in flour (**Guo *et al.*, 2012; Li *et al.*, 2016*;* Xu *et al.*, 2018**).

Pleadin *et al*. (2017) have displayed that in natural cereals and cereal-based items coming from Croatia and Bosnia and Herzegovina, the proportion of defilement with T-2 extended from 26.9% to 81.6%. T-2 mycotoxin atomic weight is 466.51 and it happens as white, needle-like gems. It contains a particular tetracyclic sesquiterpenoid 12,13-epoxytrichothec-9-ene ring in common, and a 12,13-epoxy ring, which features a pivotal work for the poisonous quality. The chemical structure is characterized by a hydroxyl (OH) bunch at the C-3 position, acetyloxy (-OCOCH3) bunches at C-4 and C-15 positions, an particle of hydrogen at C-7 position, and an ester-linked isovaleryl [OCOCH2CH(CH3)2] gather at the C-8 position (**Adhikari *et al.*, 2009; Sun *et al*., 2020**).

I.6.2.8. Deoxynivalenol (DON)

Deoxynivalenol (Wear), too known as vomitoxin, is primarily created by *Fusarium graminearum* and *F. culmorum* (**Kushiro *et al*.,2008; Tian *et al*.,2016**). These organisms are fundamental plant pathogens, which develop on field crops and cause a malady called Fusarium head scourge (FHB). Wear can sully different sorts of nourishment or bolster and natural grains, particularly in mild locales. Wear is one of the foremost as often as possible happening

mycotoxins in European nourishment and bolster. In addition, 25% of worldwide crops generation is considered to be sullied with this poison. The most elevated level of this poison is watched in maize, wheat, and inferred items (**Behrens *et al*., 2015; Huang *et al*., 2019; Wang *et al*., 2019**). The chemical title of Wear is 12,3-epoxy-3α,7α,15-trihydroxytrichothec-9-en-8-on (**Figure 5**). The atomic structure contains 3 free hydroxy bunches, which are related with its harmfulness. It takes after colorless, fine needles, dissolvable in water and polar natural solvents (ethanol, methanol, chloroform, acetonitrile) (**Sobrova *et al*.,2010**). Wear remains steady in tall temperatures, and at 150–170 °C, the poison isn't killed **(Huang *et al*., 2019**). **Table 1** summarizes their occurrence, toxicity, and fungal sources.

Table 1. list of the most common mycotoxins and their maximum levels in diet and feed **(Torelli *et al*.,2012)**

Mycotoxin	Fungal species	Food commodities	US FDA (µg/Kg)	EU (µg/Kg)
AFB1,AF B2, AFG1,AF G2	*A. flavus* *A. parasiticus*	Maize, wheat, rice, peanut, sorghum, pistachio, almond, ground nuts, tree nuts, figs,cottonseed, spices Milk, milk products, Meat	20 for total	2 - 12 for B1 4- 15 for total
AFM1	Metabolite of AFB 1	Cereals, dried vine, fruits, wine, grapes, coffee, cocoa, cheese	0.5	0.05 in milk 0.025 in infant formulae and infant milk
OTA	*A. Ochraceus* *A. carbonarius* *P. verrucosum* *P.Nordicum*	Maize,maize products, sorghum, asparagus	Not set	2 - 10 for EU
FB1 FB2 FB3	*F.verticillioides* *F. proliferatum*	Cereals,cereal products,maize, wheat, barley	2000 -4000	2000 - 4000
ZEN	*F.Graminearum* *F.roserum* *F.culmorum* *F.Equiseti,* *F.cerealis*	Ceareals, cereal products	Not set	20 - 100
Trichothecenes (Type B: DON PAT	*F.verticillioides* *F. incarnatum* *F.Graminearum* *F. culmorum* *F. cerealis*	Apples, apple juice and concentrate pears, peachs, grapes, apricots, olives low acid fruit juice	1000 50	200 - 500 10 - 50 for EU
Trichothecenes (Type A: T-2 toxins)	*P. Expansum* *Bysoclamusnivea* *A. clavatus* *p.patulum* *p. crutosum*	Maize, wheat, barley,oat, rye	15	25 - 1000
Trichothecenes (Type A: HT-2)	*F. langsethiae* *F.sporotrichioides* *F. langsethiae* *F. sporotrichioides* *F. tricinctum* *F. avenaccum*	Maize, wheat, barley, oat, rye Corn	15	25 – 1000
Enniatins(ENNs)		Rye, rye-containing commodities,	Not set	Not set
Eas	*Claviseps purpurea* *claviseps fusiformis* *claviseps africana* *Neotyphodium* spp	wheat,tritical, barley, millet and Oat	Not set	Not set

Alternariol (AOH)	*Alternaria alternata*	Grain and grain-basedproducts, vegetables,	Not set	Not set

I.6.2.9. Other common mycotoxins

Ergot alkaloids (EAs) are a bunch of mycotoxins decided from living beings of the lesson Claviceps, most extraordinarily *C. purpurea* (**Topi *et al.*, 2017**). They can besides be biosynthesized by certain Epichloë parasitic species, such as *E. coenophiala* (**Guerre *et al.*, 2015)**. EAs have a put to the course of indole alkaloids and are transcendently experienced in wheat, rye, and distinctive cereals (**ittlemier *et al.*, 2015)**. Over 80 EAs have been recognized from a run of characteristic sources, basically from Claviceps parasites, as well as from other parasitic species and plants (**Kren *et al.*, 1999**). Extraordinary EAs join ergometrine, ergocristine, ergosine, ergotamine, ergocornine, and ergocryptine, which are as frequently as conceivable recognized (**Agriopoulou *et al.*, 2020; Shi *et al.*, 2019**). EAs are known to intruded with the central anxious system (**Mulac *et al.*, 2011**), and presentation to these substances can result in honest to goodness mental and physiological impacts. In animals, EAs may lead to a reduce in effectiveness and genuine prosperity issues, tallying the runs, gangrene of the limits, untimely birth, and interior passing on (**Menzies *et al.*, 2015; Shi *et al.*, 2019).**

Tremorgenic mycotoxins are bunch of mycotoxins that cause shakings, ataxia, muscle tremors, and disarray, in some cases coming about in passing. Tremorgenic mycotoxins are a challenge to agriculture/livestock, causing numerous neurological conditions by and large named "staggers syndrome". Tremorgenic mycotoxins posture wellbeing concerns to people, illustrating neurological conditions like seizures, tremors, mental disarray, and indeed passing. Clinical signs may either be gentle, extreme, or life threatening (**Bradford *et al.*, 1990; Boysen *et al.*, 2002)**. Mycotoxins in this gather incorporate *territrems A* and *B*, which are delivered by the organism *A. terreus*, and *roquefortine C* and *penitrems A* and *E*, created by contagious species of the *Penicillium* class, particularly *P. crustosum* (**Eriksen *et al.*, 2010**).

Fusarins (*fusarins A–F*) are a course of mycotoxins with a pentane chain with a 2-pyrrolidone moiety substituted. Fusarins are created by the species of *Fusarium*, such as *F. verticillioides* (once in the past *F. moniliforme*), *F. graminearum* (*F. venenatum), F.poae, F. sporotrichioides*, and *F. oxysporum* (**Maragos *et al.*, 2007; Vettorazzi *et al.*, 2016**). *Fusarin C* is among the foremost broadly considered fusarin mycotoxins, found in creature nourishes as well as foods, and it is additionally mutagenic after it has experienced metabolic actuation (**Behrens *et al.*, 1995; Kleigrewe *et al.*, 2012;Maragos *et al.*, 2007**). A mycotoxin delivered by the species of Arthrinium, 3-nitropropionic corrosive (3-NPA) mediates mitochondrial electron transport through the irreversible hindrance of succinate dehydrogenase (Complex II), driving to a

shortfall in cellular vitality **(Behrens *et al*., 1995; Peraica *et al*., 1999; Patoˇcka *et al*., 2000**). In creatures, 3-NPA harms the fringe nerves, spinal tracts, hippocampus, and basal ganglia **(Ludolph *et al*., 1991**). Moreover, 3-nitropropionic corrosive was related with a condition called "moldy sugarcane poisoning", which is detailed to have happened around 1972 to 1988 in China's 13 territories. This was accepted to be due to the utilization of the as of now mold-infested sugarcane no less than two months post-storage. Indications showed generally 3 h post-consumption of mold-infested sugarcane as intense encephalopathy and hence as deferred dystonia, generally in youthful grown-ups and children. Inebriation comes about in irreversible generalized dystonia in a few children. Others displayed side effects after intense inebriation, counting writhings, carpopedal fits, dystonia, stomach torment, loose bowels, spewing, and queasiness, coming about in a coma and indeed passing. Inebriation in grown-ups generally driven to issues in the gastrointestinal tract and encephalopathy was exceptional. It is, in any case, obscure on the off chance that this variety can be attributed to the higher sugarcane level more often than not devoured by children or in case it mirrors the contrasts in susceptibility/vulnerability (**Ludolph *et al*., 1991; Behrens *et al*., 1995; Peraica *et al*., 1999**).

Cyclochlorotine could be a auxiliary contagious metabolite delivered by *P. islandicum*. In creatures, it is hepatotoxic and in vitro ponders on myoblasts have shown that cyclochlorotine would hinder the myofibrils to create alpha-actinin totals and islands of myosin (**Ueno *et al*., 1992; Zhou *et al*., 1994**). *P. islandicum* moreover produces another mycotoxin known as luteoskyrin, which shows up routinely in rice and has been appeared to raise the serum transaminases, harm the hepatocellular layer, and cause lipid peroxidation in mice (**Vidal *et al*., 2019**). *P. islandicum* moreover produces rubroskyrin, which discourages the mitochondrial breath in rodent livers *P. islandicum* too produces rugulosin, a hepatotoxin in creatures(**Masuda *et al*., 1992; Mori *et al*., 1996; Vidal *et al*., 2019**) **.**

Pithomyces chartarum produces *sporidesmin*, a mycotoxin that has a place with epidithiopiperazine-2,5-dione parasitic poisons (**Upreti *et al*., 1993; Zhong *et al*., 2018**). Due to the hydrophobicity of *sporidesmin*, it can be coordinates effortlessly into the cell films, where it changes the bilayer organization (**Upreti *et al*., 1993**). Ponders conducted in sheep appeared the organization of sporidesmin through the verbal course causes obsessive changes in numerous organs, body weight diminishment, liver harmfulness, facial skin inflammation, and photosensitization (**Smith *et al*., 2000**). Basically, sporidesmin seem moreover influences dairy animals and bring about high levels of the mycotoxin, which seem show up within their mains of apparently unaffected creatures. The poisonous quality of *sporidesmin* tends to be aggregate with

great variations based on individuals' defenselessness **(Smith *et al.*, 2000)**. Also, sporidesmin can create hydrogen peroxide, hydroxyl radicals, and superoxide radicals **(Munday *et al.*, 1987)**.

I.7. Factors affecting mycotoxins production

Parasites are subordinate on oxygen due to their aerobic nature; hence, organisms got to confront the consequences of oxygenic conditions such as nearness of receptive oxygen species. The receptive oxygen species are delivered amid metabolic forms and their generation can be impacted by natural stretch (**Halliwell & Gutteridge, 2007**). The collection of receptive species can potentiate m orphological and metabolic moves in organisms which in turn can result in poison blend (**Reverberi *et al.*, 2010**). **Miller (2001)** detailed that auxiliary metabolites are created from one of the essential metabolites due to impediment of one or more supplement. Proline, asparagine and tryptophan can increment the biosynthesis of AFs in *A. parasiticus* (**Reverberi *et al.*, 2010**). However, their nearness can diminish the generation of AFs in *A. flavus* (**Wilkinson *et al.*, 2007**). Temperature, pH, water action and different other natural factors altogether influence the generation of mycotoxins such as OTA and AFs (**Chein *et al.*, 2019**). The environment-based components impact the mycotoxin blend at translation level and indeed the presentation of problematic amounts of fungicides can potentiate the biosynthesis of mycotoxins (**Schmidt-Heydt *et al.*, 2007**). The nature and generation amount of mycotoxins are primarily affected by synergies of different variables:

Accessible sustenance, temperature, sorts of substrate, dampness substance conditions, stickiness, colony maturity, co-occurrence of mycotoxins with other organisms, and competing with other organisms and stretch components (**Rao, 2001**).

I.8. Impacts of mycotoxins on the economy

The coordinate showcase costs of misplaced commerce or poorer incomes as a result of polluted nourishment or nourish can be considered the financial results of mycotoxins on human society **(Raˇsi´c *et al.*, 2019**). This happens in frameworks that screen the nearness of mycotoxins in nourishment and nourish supplies (**Heussner *et al.*, 2015**). Nourishment with mycotoxin levels past a indicated greatest permitted level is either rejected through and through or sold at a lower cost for a distinctive reason in neighborhood markets or indeed on a worldwide scale As a result, nourishment makers confront gigantic monetary misfortunes Figure 6 (**Chu *et al* ., 1977**). Due to its area close the equator, which makes it especially favorable to the increase of my cotoxigenic organism species, Africa is the foremost affected of all landmasses.

Destitution and climate alter are two other factors that are complicating the continent's mycotoxins issue. In Africa, the financial effect of mycotoxins can be felt in in general human and creature wellbeing, maintainable improvement, nourishment security and security, harm to Africa's rural send out brand, diminished self-sustainability, and expanded dependence on remote help, not to say the tall taken a toll of investigate, moderation, and control of mycotoxins' predominance. Economics of mycotoxins Within the past, the science and financial matters of mycotoxins have been considered independently, but on the off chance that the mycotoxin issue is to be tended to, a adjusted thought is required of the broader results of these natural contaminants **(El-Sayed *et al*.,2022**).

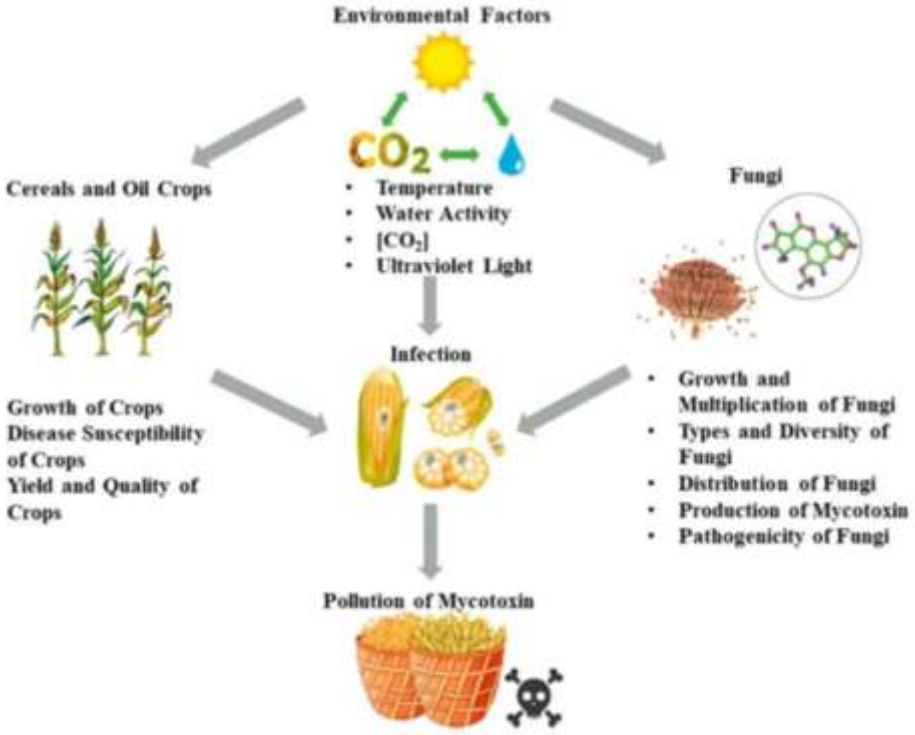

Figure 6 : Impact of environmental factors on toxin contamination **(Medina *et al*.,2015; Yao *et al*.,2021).**

I.9. Toxicological effects of mycotoxins

Effect on human and creature wellbeing (hepatotoxicity, nephrotoxicity, carcinogenicity, immunosuppression, etc.). Mycotoxins are well set up poisonous metabolic substances delivered when parasites attack agricultural/farm deliver, and this happens particularly when the conditions are favorable. Presentation to mycotoxins can specifically take put through the utilization of

tainted nourishments and bolsters; people can moreover be in a roundabout way uncovered from expending creatures bolstered with contaminated nourishes. Among the hundreds of mycotoxins known to people, around a modest bunch have drawn the foremost concern since of their event in nourishment and serious impacts on human wellbeing **(WHO, 2021**).

AFB1 and OTA are the foremost harmful mycotoxins to creatures and people. AF1 is the most carcinogenic mycotoxin and can enter cell layers, in this way connecting to DNA where it causes genomic adjustments. Understanding the mycotoxins' toxicological components related with people and creatures still remains an imperative perspective of open wellbeing and natural concern. Through this amalgamation, we have learned more almost the mycotoxins' toxicological instruments related with people and animals. In specific, we have developed our understanding approximately how the mycotoxins' toxicological instruments effect on the human cellular genome. For accentuation, the major mycotoxins related with nourishments, humans, and animals, counting AFs, CIT, OTA, FBA, PAT, ZEA, NIV, DON and ergot alkaloids, must be taken exceptionally truly.

Moreover, illustrated that a number of these mycotoxins can be carcinogens, nephrotoxins, mutagens, etc., as they can impede human development and wellbeing represented in Figure7 and Table 1 (**IARC, 2021).** Co-exposure to genotoxic AFB1 and FBs, which may actuate regenerative cell expansion, is of wellbeing concern, but due to the stamped contrasts in their modes of activity the combined impacts are improbable added substance of the FB-analogues, FB1 is the foremost overwhelming, comprising about 70% of the overall FB contamination. FB2 and FB3 co-occur with FB1 but with lower concentrations. Verbal exposure to FBs actuates a wide run of antagonistic impacts, with not-able species contrasts. Liver is the target organ for FB-mediated harmfulness in mice and kidney in rats, whereas in steeds equine leukoencephalomalacia and in pigs porcine pulmonary edema with signs of liver harmfulness can happen. FB1, FB2,FB3 and FB4 and their altered shapes have comparable toxicological profiles, but the potencies of the adjusted shapes are lower. FB1 is conceivably carcinogenic to people, and an affiliation between incessant dietary exposure and human esophageal and liver cancer has been claimed, but causality has not been confirmed **(Abdel-Wahh,2010; Yvv, 2016; Agriopoulou, 2020).**

Table 2. Toxic effects of mycotoxins in various food products.

Mycotoxins	Fungi	Foods	Toxicity	References
AF (B1,B2,G1,G2,M1,andM2)	***Aflavus,*** ***A.parasiticus,*** ***A.nomius,*** ***A.pseudotamarii,*** ***A.ochraceoroseu,*** ***A.bombycis*** ***A.ochraceus,*** ***A.niger,A.carbonarius,***	Cereal grains ,legumes, fruits, vegetables, and peanut	Hepato cellular carcinoma ,mutagenical teratogenic effects AFM1 causing abnormalities in fetal development	**Frisvad *et al*.(2019);Chu *et al* .(1977) ; Richard *et a*l.(2007)** **Malí˘*et al* .(2003) ; Ismaiel *et al*.(2015);Tao *et al* .(2018); Bayman *et al*.(2002)**
OTA, OTB, And OTC	***P.nordicum,*** ***P.viridicatum,*** ***P.verrucosum***	Cereals, legumes, fruits, vegetables, nuts	OTA exhibits hepatotoxic, neurotoxic, teratogenic, and nephrotoxic properties ,causingnephropathyinpigs.OTA is associated with renal failures ,interstitial nephropathy, urothelial tumors, and BEN in humans.	**Tao *et al*.(2018)**
FB1,FB2,FB3	***F.oxysporum*** ***F.nyagamai*** ***F.proliferatum*** ***F.graminearum*** ***FculmorumF.***	Corn, beans, soybeans, sorghum, rice,oats	Inhibiting sphingolipid synthesis Linked to esophageal and liver cancers in people. In monkeys, associated with ELEM. In horses, causing respiratory inflammatio	**Marin *et al*.(2013)**
Trichothecenese.g.,DON,T-2/HT-2toxins	***F.poae,*** ***F.langsethiae,*** ***F.sporotrichoides*** ***Trichodera*** ***Stachybotrys*** ***Trichothecium***	Corn, wheat, barley, and animal-based foods like eggs, kidney ,and milk	T2 toxins and DON permeate cellular membranes, hindering the translation process by interacting withribosomes.T2 toxins exposures cause ATA in humans.	**Landoni *et al*.(2020)Patocka *et al*. (2018) ; Nathanail *et al* .(2015) ; Klaban *et al*.2021)**
	F.cerealis	Corn, wheat, oats,barley,	It also hinders the production of DNA, RNA, and proteins, causing apoptosis, lipid peroxidation, and cytokinesis.	**Conkov´ *et al*.(2003) ;Mazaheri *et al*. (2021)**

ZEA	***F.graminearum***	rye	ZEN induces liver cancer, tumors in the uterus, and thyroid adeno main rats. ZEN causes testicular atrophy, retinopathy ,nephropathy ,and cataractsinrats. ZEN regulates enzyme expression with in biosynthetic pathways.	**Malíˇ *et al*.(2003)**
	F.equiseti,			
	F.culmorum,			
	F.vertillioides			
	P.expansum	Apples, apple products, cereals, legumes, seeds, fruits, nuts, vegetables	PAT induces carcinogenicity, mutagenicity, teratogenicity, and neurotoxicity effects in humans .PAT exhibits immunotoxic and neurotoxinc properties in animals	**deChampdore.*et al*.(2007) ; Frisvad *et al*.(2018)**
PAT	***P.patulum***			
	P.urticae			
	P.crustosum			
	P.griseofulvum			

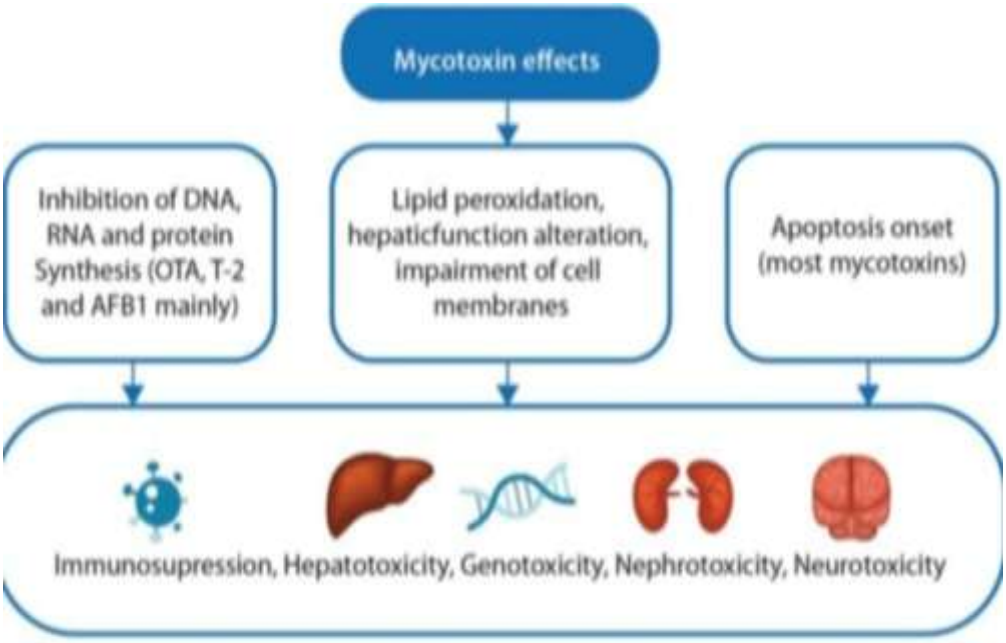

Figure 7 : Effects of Mycotoxins

- **Hepatotoxicity**

The liver is the essential target organ for AFs. Intense presentation can lead to liver harm, showing as jaundice, stomach torment, and raised liver chemicals. Serious cases can advance to liver disappointment, which may be deadly. The hepatotoxic impacts are regularly credited to the bioactivation of AFs to receptive epoxide intermediates, driving to cellular harm and rot (**Benkerroum *et al*., 2020**).

- **Safe Framework Concealment**

AFs can impede safe function, making individuals more vulnerable to contaminations. This is especially concerning in newborn children, who as of now have juvenile safe frameworks. Resistant concealment can lead to higher rates of dreariness and mortality from irresistible infections (**Benkerroum *et al*., 2020**).

- **Cancer risk associated with mycotoxins**

Epidemiological prove unequivocally underpins the connect between mycotoxin presentation and expanded cancer chance, especially liver cancer due to AFs and

esophageal and kidney cancers from FUMs (**Mulisa*et al*., 2025**). Populaces in locales with tall defilement and restricted nourishment security measures are at hazard. This underscores the pressing requiree for viable monitoring, regulatory measures, and nourishment security mediations to decrease introduction to mycotoxins and moderate their related cancer dangers

Administrative limits and chance appraisal (WHO, FAO, EFSA, FDA standard National and universal educate and organizations, such as the European Commission (EC),the US Nourishment and Medicate Organization (FDA), The World Wellbeing Organization (WHO) and the Nourishment and Horticulture Organization (FAO) of the Joined together Countries, have recognized the potential wellbeing dangers to creatures and people postured by nourishment and feed-borne mycotoxin inebriation and tended to this issue by receiving administrative limits for major mycotoxin classes and chosen person mycotoxins. The FAO has compiled comprehensive around the world directions and mandates with respect to mycotoxins in nourishment and bolster as of December 2003 (**FAO 2004**).The Joint Master Committee on Nourishment Added substances (JECFA), a logical counseling body of FAO and WHO, gives components for surveying the harmfulness of nourishment added substances, veterinary sedate buildups and contaminants, and has as of late assessed the dangers related to a few mycotoxins, counting FUMs B 1 , B 2 and B 3, OCT A, DON, T-2 poison, HT-2 poison, and AFM1 **(WHO , 2002).** The report clarifies the nature of each poison, counting its retention and excretion, as well as toxicological ponders, and it incorporates common contemplations of explanatory strategies, inspecting, related admissions issues and control instruments **(Christian , 2007**)

Due to mycotoxins' wellbeing dangers and financial impacts, administrative bodies built up rigid rules and limits for mycotoxin levels in nourishment and creature nourish. International organizations just like the Codex Alimentarius, in collaboration with the WHO and the FAO, set worldwide benchmarks pointed at minimizing mycotoxin defilement and ensuring open health (**Sirma *et al.*, 2018)**.

These administrative endeavors are basic in guaranteeing nourishment security; however, challenges stay in achieving comprehensive control over all stages of the nourishment generation process (**Lamm *et al*., 2021**).

In outline, mycotoxins delivered by molds that develop on different crops speak to a critical concern in nourishment security due to their harmful impacts on wellbeing, counting the potential to cause cancer. The financial suggestions of mycotoxin defilement encourage complicate nourishment security and exchange. Compelling observing, control measures, and worldwide administrative benchmarks are vital in relieving the effect of mycotoxins on open wellbeing and the worldwide nourishment supply chain (**Huong *et al*., 2019**).

Mycotoxins are pivotal due to their noteworthy effect on open wellbeing and nourishment security, especially their affiliation with cancer chance. Mycotoxins, such as AFs, are exceedingly powerful carcinogens and are straightforwardly connected to liver cancer, among other wellbeing issues.

The Universal Office for Inquire about on Cancer (IARC) has classified AFs as Gather 1 carcinogens, showing clear prove of their cancer-causing potential in humans **(Soni *et al* ., 2020). Such** poisons, created by organisms that sully staple nourishment crops like maize, peanuts, and grains, can gather within the nourishment chain, posturing unremitting wellbeing dangers when devoured over time. Subsequently, standard nourishment examination and checking of mycotoxins are basic to anticipate long-term introduction that may raise cancer dangers, especially in defenseless populaces with constrained dietary diversity (**Huong *et al*., 2019)** .

The synergistic intelligent between different mycotoxins, in conjunction with other environmental and dietary components, altogether open up their harmfulness and complicate open wellbeing dangers. Different mycotoxins frequently co-occur in sullied nourishment or nourish, such as AFs and FUM in maize, where their combined nearness improves the carcinogenic potential past the impacts of each poison alone. This synergism not as it were compounds liver cancer hazard but too increments the probability of other unfavorable wellbeing results, including immunosuppression and impeded development. Variables like measurements and presentation levels advance impact this synergism, where moo dosages of numerous mycotoxins can have improved impacts than higher dosages of a single one.Metabolic intelligent moreover play a part, with the metabolites of one mycotoxin potentially upgrading the poisonous impacts of another. The resistant framework, regularly smothered by certain mycotoxins, gets to be more helpless to advance poisonous affect, whereas disruptions in intestine microbiota and disabled detoxification forms can increment helplessness to different mycotoxins. Dietary lacks, especially in basic supplements like proteins, vitamins, and minerals, compound these impacts

by lessening the body's capacity to detoxify mycotoxins, expanding defenselessness to constant infections, counting cancer **(Tolosa *et al*., 2021)**.

Also, mycotoxins can meddle with liver chemicals dependable for detoxification and initiate oxidative stretch, debilitating the body's guards against poisons. Understanding these complex intelligent is pivotal for compelling chance appraisal, nourishment security interventions, and developing methodologies to relieve the wellbeing dangers related with numerous mycotoxin exposures (**Abraham *et al*., 2022**).

In expansion to cancer dangers, mycotoxins show broader nourishment security concerns that require careful examination. Sullied nourishments can lead to a run of wellbeing issues past carcinogenicity, counting safe concealment, gastrointestinal disarranges, and regenerative issues (**Kortei *et al*., 2023)**. These impacts are especially concerning in locales with destitute nourishment security foundation, where sullied nourishments may be broadly expended due to constrained direction or inadequately post-harvest administration. Guaranteeing nourishment security through analyzing mycotoxin levels makes a difference relieve these wellbeing dangers and protect consumers and the worldwide nourishment supply chain (**Nada *et al*., 2022)**. Hence, successful mycotoxin administration is significant in nourishment security and cancer anticipation and maintaining financial reasonability within the nourishment industry **(Agriopoulou *et al*., 2020)** .

I.10.Mycotoxins contamination

Mycotoxins are noxious, omnipresent in chemical nature compounds, created by different parasites species, whose event within the nourishment chain is unavoidable and postures a genuine issue on a worldwide scale **(Pinton *et al*., 2014).** Human introduction to mycotoxins is common due to nourishment and bolster defilement (**Da Rocha *et al*., 2014**). Mycotoxins defilement can result from destitute clean conditions amid collect, transport, preparing, or capacity as well as unfavorable climate. In expansion to utilizing great sanitation measures, it would be great hone to make mindfulness of the harmful impacts of mycotoxin harming in people and animals (**Magan *et al*., 2007; Edwards *et al*., 2018**). Contagious defilement postures a genuine risk to human and creature wellbeing, which, depending on measurements and time of exposure, can lead to different afflictions. The digestive tract is the primary obstruction to nourishment contaminants and the gastrointestinal tract is the primary target of mycotoxins (**Pinton*et al*., 2012**). Various ponders centering on the harmful activities of mycotoxins have

appeared that ingestion of contagious poisons may result in a assortment of impacts. It has been detailed that mycotoxins are poisonous to the anxious, safe, and regenerative frameworks (**Hou *et al.*, 2018**). A overview of mycotoxin components of activity on the human living being is displayed in Figure 8. Separated from human and creature wellbeing risk, defilement of agrarian crops with mycotoxins contributes to noteworthy financial misfortunes (**Mitchell *et al.*, 2016**). The European Commission has evaluated that 5–10% of worldwide trim misfortunes are caused by mycotoxins, causing the misfortune of 2.4 billion Euro in Europe **(Janssen *et al.*, 2019)**. Future inquire about ought to center on creating information on epidemiological impacts and long-term poisonous quality, particularly in people.

The advancement of cheap mycotoxin discovery disobedient that are versatile, solid, and simple to use within the field is additionally an viewpoint to be famous. An interesting arrangement may be the improvement of modern, hereditarily adjusted plants that can be safe to contagious intrusion. To preserve financial steadiness and agriculture, it may be advantageous to create unused conventions and strategies to compare the costs and benefits of diverse measures to combat parasitic pathogens.

I.11. Metabolism of Mycotoxins

Mycotoxin metabolism involves biotransformation processes primarily in the liver, where these toxins undergo phase I (oxidation, reduction, hydrolysis) and phase II (conjugation) reactions. These metabolic pathways can either detoxify the mycotoxins or, in some cases, produce more toxic metabolites.

I.11.1. Aflatoxins' Metabolism: Biochemical, Molecular and Cell Signaling Aspects

After ingestion of sullied nourishment, AFs are retained within the digestive tract; taking after their dispersion, digestion system and excretion, the liver is the primary and fundamental organ influenced Figure 9. They moreover collect in muscle. P450 cytochromes play an critical part in stage I biotransformation of xenobiotics, particularly those having a place to families 1 and 3 **(Antonissen *et al .*, 2017**). In warm blooded creatures, the chemicals with the highest levels of protein expression, and included within the transformation of AFs, are CYP1A2 and CYP3A4. The metabolite coming about from the oxidation response can tie to DNA, causing genotoxicity, and proteins creating cytotoxicity. For case, AFB1 ties to guanine buildups of nucleic acids, coming about in AFB1 adducts that can lead to transversion of guanine–cytosine (GC) to thymine–adenine (TA) and implicitly to irreversible DNA harm. Official of AFB1 to

proteins is irreversible, the foremost well-known adduct being ADB1-lysine in egg whites. Within the to begin with organize of metabolic oxidation within the liver, an epoxy responsive middle of the road (e.g., AFB1-8,9-epoxide) is shaped or usually hydrolyzed to a less harmful shape, AFM1 **(Allocati *et al*.,2018).**

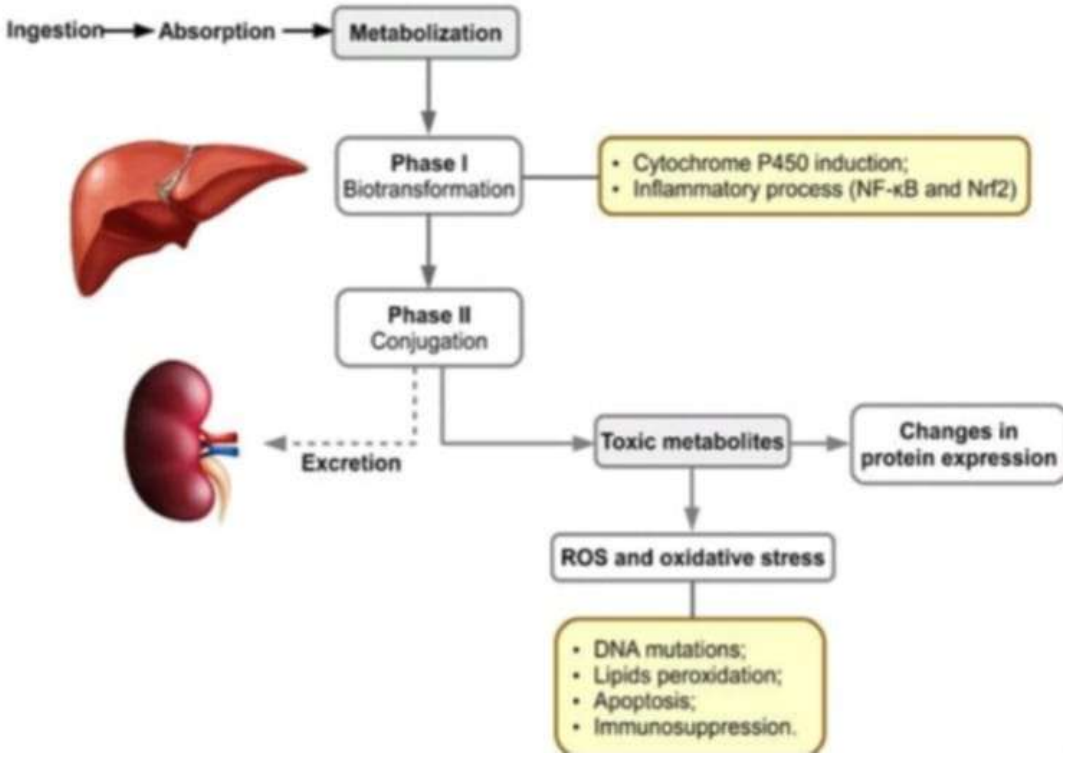

Figure 8 : The adverse cellular effects of mycotoxins and their metabolite **(Antonissen *et al*., 2017 ; Mulero et *al*., 2015 ; Jarolim et *al*., 2017, Wen *et al*., 2016).**

The cytochrome P450 super family comprises of chemicals included in xenobiotic digestion system and endogenous compound oxidation; in this way, Stage I proteins catalyze the responses of hydroxylation, sulphoxidation, epoxidation, N-, O- and S-dealkylation, oxidative fragrant hydroxylation, desulfuration, denitrosation, and dehalogenation pointing for the expansion of utilitarian polar group(s). In porcine hepatic tissue, the CYP450 proteins communicated are spoken to by CYP2A19 (34%), CYP2D25 (25,5%), CYP2C49 (11.2%), CYP2E1 (8.1%), CYP3A39 (8,1%), CYP3A29 (5,8%), CYP2C33 (5%) and CYP1A2 (2.3% of the entire liver CYPs, individually) **(Nannelli *et al*., 2008;Kojima *et al*., 2004; Shang *et al*., 2009; Puccinelli *et al*., 2010 ; Yao *et al*., 2011; Achour,2012 ;Burkina *et al*., 2019).**

Stage II of digestion system involves conjugation responses of metabolites already shaped **(Lehman-McKeeman *et al*., 2018)** with glucuronic corrosive and sulfate particularly. Hence,

the epoxide metabolite produced in stage I may be detoxified in stage II by glutathione conjugation, through hydrolysis by an epoxide hydrolase to AFB1-8,9-dihydrodiol, or by decrease to a less poisonous metabolite such as AFM1 or AFQ1 (**Gallagher *et al*., 1996; Bennett *et al*., 2003; Dhama *et al*., 2007, Diaz *et al*., 2010; Devreese *et al*., 2013)**. The coming about metabolites are excreted through the biliary pathway, taken after by the urinary pathway.

By RNA-seq innovation it was demonstrated that in vitro introduction of bovine fetal hepatocyte cell line (BFH12) to AFB1 influenced the cells' transcriptome. Hole intersection protein beta 2 and Follistatin gene the last mentioned being included in multiplication and colony development of forebear populaces of hepatocytes as well as those of ornithine decarboxylase and A-Raf proto-oncogene have been up regulated. Instep, qualities that codify for tumor silencers, such as those of collagen sort XVIII alpha 1 chain (COL18A1), collagen sort 1 alpha 2 chain (COL1A2), as well as that for natriuretic peptide receptor 3 have been down regulated. The treatment with this mycotoxin too up regulated the taking after CYP isoforms: CYP26B1, CYP3A4, CYP27B1 and down regulated CYP1A1, CYP1B1, CYP19A1, CYP36A1, CYP4B1 (**Pauletto *et al*., 2020**).

The same ponder from **Pauletto *et al***. (**2020**) uncovered that all analyzed glutathione-S-transferase qualities, but those for omega 1 and pi1 isoforms, have been down regulated. The quality sets for TNF-α signaling through NF-kB, oxidative phosphorylation, DNA repair, incendiary reaction, KRAS signaling, p53 pathway, PI3K-Akt-mTOR signaling, apoptosis and hypoxia have been up regulated by AFB1 treatment of BFH12 cells. Within the same conditions, other quality sets for epithelial–mesenchymal move, bile corrosive digestion system, estrogen reaction and heme digestion system have been down regulated.

As of late, based on transcriptomic information and post translational investigations, it was hypothesized that Toll-Like Receptor (TLR2) actuation is included in AFB1-induced irritation and oxidative push in BFH12 cells (**Iori *et al*., 2022**). In addition, in a chicken hepatocarcinoma cell line (LMH) uncovered to AFB1 differentially, expression investigation uncovered that 1006 qualities have been up regulated and 791 down regulated, compared with the control treatment. The mRNA expression of CYP27A1, CYP1A4, FABP2, PPARα and GSTT1 were essentially diminished by this mycotoxin treatment, while qualities mindful for central grip and MAPK pathways were up regulated compared with control ones **(Choi *et al*.,2020).**

Already it was taken note that in HepG2 cells treated with AFB1, increments within the expressions of miR-34A and miR-33a-5p driven to an imperative diminish of β-catenin, c-myc and cyclin D1 levels within the Wnt signaling pathway, producing an vital hazard of hepatocellular carcinoma **(Tooth *et al* ., 2013; Zhu *et al*., 2015).** The introduction to this mycotoxin moreover restrains protein amalgamation and due to this, enzymes' levels of distinctive metabolic pathways are influenced **(Caloni *et al*., 2011).**

As of late, it was demonstrated that AFB1 presentation of cells influences the respiratory chain, producing receptive oxygen species (ROS). In the event that these are not checked by the antioxidant enzymatic and non-enzymatic frameworks, oxidative stretch happens (**Ma *et al*., 2021)**. The overabundance of ROS assaults polyunsaturated greasy acids from glycerophospholipids, producing conclusion items of lipid peroxidation, as well as DNA and proteins. Lipid peroxidation and oxidative damage to DNA play a major part within the harmfulness of AFs.

The framework capable for the biotransformation of AFB1fundamentally has five instruments, spoken to by responses of lessening, hydration, epoxidation, hydroxylation and orthodemethylation. The aflatoxicolis delivered by diminishment of AFB1 by an NADPH-dependent cytoplasmic chemical show within the dissolvable division of the liver. The harmfulness of aflatoxicolisclearlymuchlittlerthanAFB1, but the change is reversible and the aflatoxicol can serve as a reservoir toxicity of AFB1 within the intra cellular space, it can be changed over in this mycotoxin by microsomal dehydrogenase. The aflatoxicol can more over bemetabolized to AFM1 and AFH1 (**Biehl & Buck, 1987**). The hydration prepare comes about in a metabolite AFB2a.This compound has the most activity the inhibition of chemicals, within the liver and other tissues, causing a diminishment in proteic amalgamation (**Ellis *et al*., 1991**).

The immaculate frame of AFB1 has no mutagenic action. The biotransformation of this compound through the response of epoxidation is that changes the AFB1 in powerful carcinogen compost. The compound shaped by epoxidation is profoundly electrophilic and can respond rapidly, through covalently with nucleophilic destinations of macromolecules, such as deoxyribonucleic corrosive (DNA), ribonucleic corrosive (RNA) and proteins (**Oliveira &Germano, 1997**). The official of 8,9 epoxides of AFswith DNA is shaped with the N7 of guanine, which decides the arrangement of adducts Af-N7-guanine within the target cell (**Lillehoj, 1991**). As a result of this adduct, the guanine-thymine (GT) combine endures a transversion in codon 249 of the p53 silencer tumor quality (**Wang &Groopman, 1999**). The

seadducts shaped within the DNA atom can be evacuated from the particle after its arrangement, clearing out empty locales, which tend to be recorded with adenine, coming about in a transformation point. The compound 8,9 epoxide of AFs is dependable by decrease in protein union and the mutagenic, teratogenic and carcinogenic effects. The authoritative of 8,9 epoxides of aflatoxin with DNA or RNA of the liver has been illustrated in vivo and in vitro (**Biehl & Buck, 1987**). The restraint of blend of flag-bearer RNA, the action of DNA-dependent RNA polymerase, of protein amalgamation within the liver and diminish in plasmatic proteinsamidaflatoxicos is cause a reduction of fat digestion system within the liver, causing rot and greasy degeneration, diminish bile stream and impeded assimilation of supplements, particularly vitamins and fundamental aminoacids (**Quezada *et al.*, 2000**). AFM1 and AFQ1 are comes about of hydroxylation response of AFB1. These compounds have a hydroxylgather, permitting their conjugation with glucuronic corrosive, sulfate and glutathione, making them exceptionally water-soluble substances that can be excreted within the bile, pee and drain (**Biehl & Buck, 1987**).

Glutathione S-transferaseis an isoenzyme that catalyzes the conjugation responses with glutathione and ensures tissues from harmful responses. The affectability of a assortment of creature species to the poisonous impacts of AFB1, in expansive portion depends on the capacity of these species to detoxify the responsive metabolites of this poison through the method of conjugation with glutathione **(Neal *et al.*, 1998).**

Most of the AFs are excreted between 72 to 96 h after the presentation, with the liver and the kidney holding the squander for a longer period compare to other tissues **(Biehl& Buck, 1987**).

I.11.2- Fumonisins

The structure of fumonisin B1 is exceptionally comparable to that of the free sphingoid base sphinganine. This had driven to the theory that FBs supply their poisonous impacts through a disturbance of sphingolipids digestion system or hindrance of the work of sphingolipids. The sphingolipids play critical parts in film and lipoprotein structure, cell-to-cell communication, interaction between cells and extracellular lattice and direction of development calculate receptors and as moment couriers for a wide extend of variables, counting the tumor corruption calculate and interleukin-1 (**Soriano *et al.*, 2005).**

The FBA induced disturbance of sphingolipid digestion system is imperative within the cascade of occasions driving to changed cell development, separation and damage watched both in vivo and in vitro (FBA disturbance of ceramide). The FBs are competitive inhibitors with respect to both substrate (that's, sphinganine and greasyacyl coenzyme A) of sphinganine (sphingosine) N-acetyltransferase (ceramide synthase). The comes about of this restraint incorporates: Blockage of complexs phingolipids biosynthesis, increment of free sphinganine and sphingosine, and reacylation of sphingosine inferred from complex sphingolipid turnover and corruption of dietary sphingolipids (**Enongene *et al*., 2000; Soriano *et al*., 2005**).

The amassing of free sphinganine initiated of growth-inhibitory and cytotoxic to cells and expanded cell passing (apoptotic and oncotic) in liver and kidney. Additionally, in creatures, utilization of FUMB1 disturbs sphingolipid digestion system as shown by the aggregation of tall levels of free sphinganine in liver, kidney, serum and/or pee (**Enongene *et al*., 2000).**

I.11.3- Zearalenones

Mycotoxins having a place to the zearalenone (ZEN) family are major cereal edit and creature bolster contaminants that are moreover normally delivered by organisms of the Fusarium sort **(Zhang *et al*., 2018) .** ZEN compounds have been connected to regenerative disarranges in warm blooded creatures due to their closeness to the female steroid hormone, 17β-estradiol (**Katzenellenbogel *et al*., 1997; Zhang *et al*., 2018).** For case, these mycotoxins may hinder imperative oestrogenic reactions or prevent steroid discharge **(Katzenellenbogel *et al*., 1997; Zhang *et al*., 2018).** Inside this mycotoxin family, it was found that α-zearalenol (ZEL) is the foremost powerful metabolite due to its raised oestrogenic action (**Niermans *et al*., 2019; Yang *et al*., 2020).** Consequently, these mycotoxins are of specific concern inside the animals industry as they can have oestrogenic impacts on swine and cattle, such as hyper oestrogenism (**Kyiper-goodman *et al*., 1987; Zhang *et al*., 2018).**Unfortunately, ZEN compounds are troublesome to treat as they can withstand temperatures of up to 160 ◦C; in this manner, elective detoxification procedures must be looked for out **(Kyiper-goodman *et al*., 1987 ;Zhang *et al*., 2018).**

When *T. molitor* hatchlings are uncovered to tall levels of ZEN, it can disturb the work of their hormone ecdysone, which is able in turn influence their advancement and shedding.

In any case, a ponder by **Niermans *et al*. (2019)** found that *T. molitor* hatchlings are versatile towards wheat crops that contain ZEN concentrations as tall as 2 mg/kg, as both the mycotoxin

and its metabolites, α- and β-ZEL, were nearly totally excreted from its framework after introduction. Inside the examination, the hatchlings were bolstered wheat sullied with 0.5–2 mg/kg of ZEN for a period of either 4 or 8 weeks**.** When the hatchlings were analyzed by HPLC-MS, the chromatograms were not able to show any traceable levels of the mycotoxin, whereas the analyzed excreta contained ZEN, α- and βZEL concentrations that coordinated the starting mycotoxin concentrations display within the nourish. These comes about concur with a think about conducted by **Camenzuli *et al*. (2018**). where *H. illucens* and lesser mealworms (Alphitobiusdiaperinus) were given nourish misleadingly spiked with 0.5–13 mg/kg of ZEN over a period of 10 days and 14 days, individually. After introduction, the creepy crawlies were given non-contaminated nourish for an extra 2 days to decide the mycotoxin collection within the larvae's body instead of the intestine after ingestion.

From the comes about, the survival and development of both creepy crawly species were not essentially affected by any of the ZEN concentrations tried.*H. illucens* hatchlings were found to metabolize over half of the ZEN devoured into α- and β-ZEL metabolites and excreted all these poisons when raised on spiked nourish as well as when cleansed on uncontaminated nourish. On the other hand, *A. diaperinus* shown negligible ZEN catabolism and were instep found to discharge nearly all of the poisonous compounds when raised on spiked bolster. In this manner, the distinctive creepy crawly species were appeared to conduct diverse detoxification procedures and not one or the other species were extremely influenced by any of the ZEN concentrations tested **(Camenzuli *et al*., 2018).**

I.11.4 - Vomitoxins

Like FBs and ZEA, vomitoxins are delivered by organisms that have a place to the Fusarium family and are a common grain contaminant **(Trenholm *et al*., 1985; Rotter *et al*., 1996).** Vomitoxin, moreover known as deoxynivalenol (Wear), may be a trichothecene that compromises the resistant framework and protein blend , and actuates oxidative push inside creature cells upon ingestion **(Jankovi´c *et al*., 2019)**. In expansion, introduction to Wear may have potential impacts on the apprehensive framework and nourishing behavior (**Rotter *et al*., 1996**). Wear defilement is troublesome to treat due to its soundness; subsequently, its nearness in creature bolster is of concern due to its impact on animals efficiency (**Trenholm *et al*., 1985 Rotter *et al*., 1996).** For occasion, whereas cattle and poultry can handle Wear introduction, steeds and swine have been detailed to deny the utilization of sullied nourish. **(Trenholm *et al*., 1985).**

A ponder by **Van Broekhoven *et al.*** (**2017**) explored *T. molitor's* resilience to Wear through its breakdown and excretion instruments. Inside this think about, *T. molitor* hatchlings were raised on wheat flour that was actually or misleadingly sullied with 4.9 and 8 mg/kg of Wear, individually, over the course of 2 weeks **(Van Broekhoven *et al.*, 2017)**. Not as it were did each of these Wear concentrations have small impact on the in general development and survival of the hatchlings, but the mycotoxin moreover did not gather inside the life forms .Examination of the defecation uncovered that the hatchlings excreted 14–40% of the Wear that was at first display within the nourish, but advance data with respect to the Wear metabolites delivered or the detoxification pathway may not be decided . In expansion, an examination by Ochoa Sanabria *et al*.**(2019)** explored the impacts of Wear on *T. molitor* when given wheat sullied with Wear concentrations extending from 2 to 12 mg/kg over the course of 30 days. In spite of the fact that there were no enduring impacts on the insect's survival or development, the larval bodies were found to contain insignificant concentrations of Wear and the metabolite 3-acetyl-DON that were on standard with the levels identified within the control hatchlings (**Ochoa Sanabria *et al.*, 2019)** The *T.molitor* hatchlings were found to as it were discharge 6–15% of unmetabolized Wear, and instep excreted higher levels of 3-acetyl-DON, highlighting the organism's metabolic detoxification capabilities . A consider by Jankovic´-Tomanic´ *et al*.**(2019)** assist extended on these comes about by expanding *T. molitor* hatchlings presentation through wheat sullied with 4.9–25 mg/kg of Wear over a period of 2 weeks. Once once more, the survival of *T.molitor* was not influenced by the presentation; in any case, the hatchlings displayed diminished motion, protein synthesis and body weight when uncovered to the most elevated Wear concentrations (**Jankovi´c-Tomani´c *et al.* 2019**). Through this ponder, it was too found that the movement of the proteins glutathione-S-transferase (GST) and superoxide dismutase (Turf) expanded relatively to the Wear introduction, in reaction to the coming about oxidative stretch and to the detoxification of the recently shaped superoxide anion radicals, separately . Moreover, a consider by Gulsunoglu *et al* **.(2018)**, *H. illucens* and *A.diaperinus* were given bolster with Wear concentrations that extended from 5 to 125 mg/kg for 10 and 14 days, individually. From the comes about, the three Wear metabolites tried, 3-, 15-acetyl-DON, and DON3-glucoside, were underneath measurement limits for both species **(Camenzuli *et al.*, 2018)**. It was too found that 39–80% of the Wear within the spiked nourish was excreted from the *H. illucens* hatchlings whereas uncovered to the poison, as well as amid the 2 days whereas raised on uncontaminated bolster (**Camenzuli *et al.*, 2018)**. On the other hand, 80–96% of the initial Wear substance was excreted from the *A. diaperinus* hatchlings whereas raised on sullied

bolster. Moreover, both ponders once once more watched that there were small to no impacts on the development, survival, and execution of the hatchlings **(Gulsunoglu *et al* ., 2019)**

I.11.5. Ochratoxins

OTAs are a bunch of mycotoxins delivered by parasites having a place the Aspergillus and Penicillium genera that commonly sully cereal crops due to the destitute capacity and dealing with of nourishment items **(Bui-klimk *et al*., 2015**). Inside this mycotoxin family, OTA is the foremost inexhaustible and poisonous shape to warm blooded creatures **(Bui-klimk *et al*., 2015; Heussner *et al*., 2015)** For occasion, the poison can influence the resistant framework ***(*Niu *et al*., 2009),** or target the kidneys and cause renal issues such as cancer or nephropathy in people and creatures alike **(Bui-klimk *et al*., 2015**). Just like the other normally happening mycotoxins, OTAs are chemically steady, and so can be troublesome and expensive to evacuate from sullied nourish. In this manner, OTA defilement in animals bolster may be a repeating issue, hence driving to a decrease in cultivate creature wellbeing and execution **(Duarte *et al*., 2011)**.

Inside the ponders conducted by **Niu *et al*. (2009)**, and **Niu *et al*. (2011**) it was appeared that both *A. mellifera* and *A. transitella* can endure tall levels of OTA. This was illustrated when *A. transitella* hatchlings were given nourish sullied with 1–50 mg/kg of OTA over a period of 14 days (**Niu *et al*., 2009**). It was appeared that *A. transitella* is generally unaffected by OTA introduction and as it were experienced negligible formative impacts after ingesting nourish with the most noteworthy contaminant levels. Essentially, *A. mellifera* hatchlings were given sweet sullied with 1–80 mg/kg of OTA for a period of 72 h . It was found that concentrations of 1 mg/kg or lower had no poisonous impacts on *A. mellifera*; be that as it may, the life forms were found to pass on inside 3 days after the persistent utilization of sweet with OTA concentrations higher than 5 mg/kg **(Niu *et al*., 2011)**. Moreover, the distribution by **Camenzuli *et al*.(2018)** talked about the OTA resistance of *H. illucens* and *A. diaperinus* when uncovered to concentrations extending from 0.1 to 2.5 mg/kg for 10 and 14 days, respectivelyIt was found that around 100% of the OTA was excreted from *A. diaperinus* when raised on both spiked and non-contaminated bolster **(Camenzuli *et al*., 2018)**. Be that as it may, as it were approximately 50% of the first OTA was accounted for within the *H. illucens* hatchlings and excreta. Shockingly, the coming about metabolites, included proteins, and detoxification instruments of OTA inside creepy crawlies have however to be recognized (**Figure 9**) **(Niu *et al*., 2009; Niu *et al*., 2010; Niu *et al*., 2011; Camenzuli *et al*., 2018).**

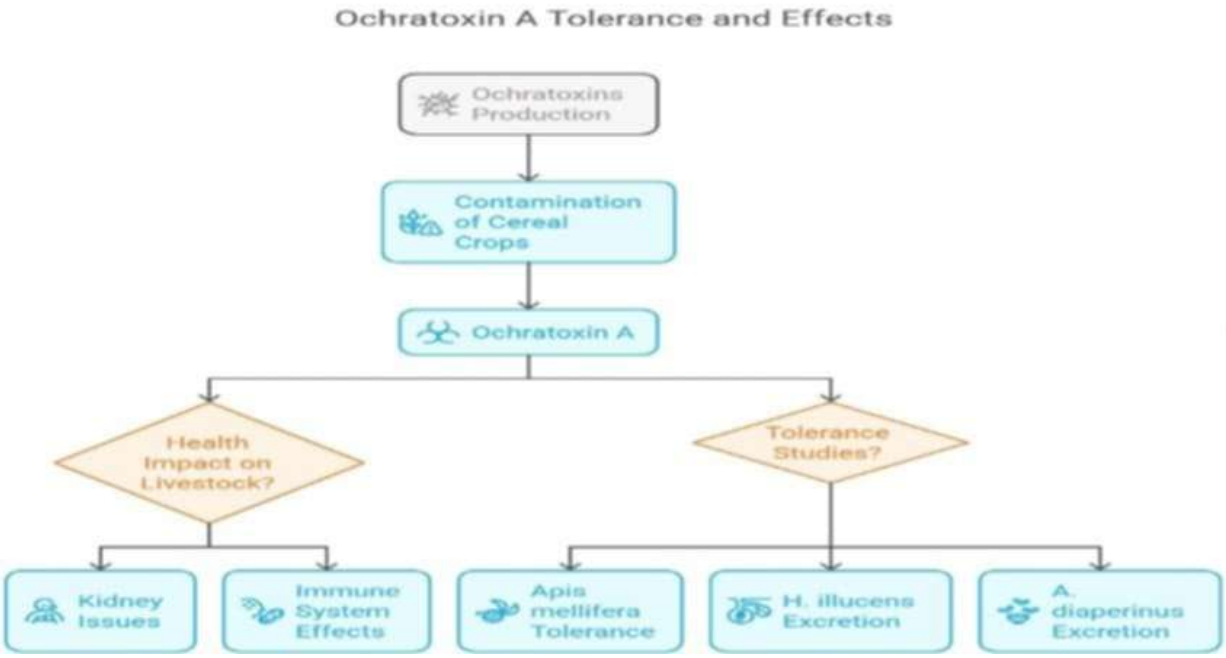

Figure 9 : Ochratoxin A tolerance and effects.

I.11.6. Trichothecenes

Compared with a few of the other mycotoxins such as AFs, the trichothecenes don't show up to require metabolic actuation to apply their organic action **(Busby & Wogan, 1981**). After coordinate dermal application or verbal ingestion, the trichothecene mycotoxins can cause quick disturbance to the skin or intestinal mucosa. In cell-free frameworks or single cells in culture, these mycotoxins cause a fast restraint of protein union and polyribosomal disaggregation (**Busby & Wogan, 1981**). Hence, ready to hypothesize that the trichothecene mycotoxins have atomic capability of coordinate response with cellular components. In spite of this coordinate impact, it is conceivable to degree the harmful energy and the digestion system of the trichothecene mycotoxins. The lipophilic nature of these poisons recommends that they are effectively retained through skin, intestine, and aspiratory mucosa (**Wannemacher & Wiener, 1997**). When trichotheceneties to dynamic polysomes and ribosomes, the peptide linkages are hindered, the start and end groupings are lessened, and the ribosomal cycle is disturbed (**Ueno, 1977).**

Other harmful impacts of trichothecenes incorporate disturbance of layer transport and work, concealment of the safe reaction, and irregular blood work. For illustration, the negative impacts of T-2 poison on cell film work were clarified by disturbing the transport of aminoacids,

nucleotides, and glucose and action of Ca–K channel **(Bunner & Morris, 1988**). **Khachatourians (1990) illustrated** that mitochondrial electron transport is additionally repressed by T-2 poison as a result of concealment of succinate dehydrogenase movement. Lipid peroxidation through era of free radicalsamid T2 digestion system has moreover been proposed as a mode of trichothecene activity in rodent liver (**Suneja *et al.*, 1989; Johannisson *et al*., 1999**). With respect to the resistant reaction, multiplication of human lymphocytes in societies was appeared to be restrained by T-2 poison, Wear, and DAS (**Suneja *et al*., 1989**). In another in vitro consider where murine peritoneal macrophages were utilized **(Ayral *et al.*, 1992**), Wear and DAS were appeared to hinder the phagocytic action, microbicidal action, and superoxide anion generation. The activities of trichothecenes at the hematologicallevel have been outlined in a few ponders (**Faifer *et al*., 1992; Lautraite *et al*., 1997; Rio *et al*., 1997**). For illustration, T-2 poison decreased granulocyte macrophage colony-forming cells within the bone marrow of mice (**Faifer *et al.*, 1992**). In another consider **(Lautraite *et al*., 1997**), Wear repressed granulo-monocytic fore bears. Both T-2 poison and DAS too repressed human erythrobalstic fore bears **(Rio *et al*., 1997**). In rundown, exceptionally small of the parent trichothecene mycotoxins is excrete intaglio. Or maybe, disposal by detoxification of the poison is the result of broad and quick biotransformation **(Wannemacher &Wiener, 1997).**

I.12.Mycotoxin regulations and legislation in food commodities

In arrange to anticipate their hindering impacts on people, mycotoxins are controlled by greatest allowable levels in nourishment (**Claeys *et al*., 2020**).The substance of mycotoxins in nourishment commodities have been limited in a few nations (**Puel *et al*., 2010**).Moreover, a number of national and universal organizations, counting the FAO , WHO , EU Commission, and Codex Alimentarius Commission, have built up controls with respect to distinctive sorts of mycotoxins display completely different nourishments pointed at securing customers (**Adeyeye, 2016**).

Most nations have no particular limits on particular nourishments or nourishment items, but all nourishment items are subject to common directions. There are, be that as it may, a few nations in Europe and the USA that have enacted dietary limits for particular nourishments. Among mycotoxins, AFs have powerful genotoxic, carcinogenic, and immunosuppressive impacts on individuals. Hence, in most nourishment commodities, government organizations have setup greatest levels of AFs, counting AFB1 (**Bhat & Reddy, 2017**).

The most extreme limits (µg/kg) of imperative contagious mycotoxins in major nourishment commodities that were enacted are summarized in **Table 3**.

Table 3. The maximum limits (µg/kg) established for major mycotoxins in some countries/regions for all food commodities

Countries	Food commodities	Mycotoxins	References
Brazil	All foods	15 (AFB1)	**Aiko & Mehta. (2015**)
Chile	All foods	200 (ZEA)	**Ji *et al*. (2019)**
China	All foods	30 (AFB1)	**Ji *et al*. (2019)**
EU	All foods	5 (AFB1); 10 (TAF); 15 (OTA)	**EC (2006)**
India	All foods	30 (AFB1)	**Anukul *et al*. (2013)**
Indonesia	All foods	35 (AFs), 20 (AFB1)	**Ji *et al*. (2019)**
Japan and Vietnam	All foods	10 (AFs)	**Anukul *et a*l. (2013)**
Malaysia	All foods	35 (TAFs)	**Srianujata (2011)**
Singapore and Australia	All foods	5 (AFs)	**Anukul*et al*. (2013);Mazumder&Sasmal (2001)**
Sri Lanka	All foods	30 (TAFs)	**Anukul *et al*. (2013)**
Thailand	All foods	20 (AFs); 30–1,000 (ZEA)	**Anukul*et al*. (2013);Mazumder&Sasmal (2001)**
USA	All foods	20 (AFs); 1,000 (ZEA); 2000 (FBs)	**Ji *et al*. (2019);Mazumder&Sasmal (2001)**
EU	Maize oil	400 (ZEA), 1,000 (FBs)	**European Commission (EU) (2006); Goud *et al*. (2020)**
China	Peanut oil	20 (AFB1)	**Selvaraj *et al*. (2015)**
Cuba	Fruits	40 (PAT)	**Cai *et al.* (2020)**
Canada	Fruits and Fruit Juice	50 (PAT)	**Canada (2020)**
India	Apple Juices	50 (PAT)	**Shukla *et al*. (2014)**
Japan	Apple Juices	30 (PAT)	**Li & Beghin (2014)**
European Union	Tomato juices	30 (PAT)	**Van Egmond & Jonker (2008)**

II. Analysis and detection of major mycotoxins in food

New technologies are constantly improving this process, making detection faster, more affordable, and more efficient. These innovations are key to ensuring food safety and reducing health risks (**Smith & Lee, 2023**).

II.1. Conventional analytical Methods for mycotoxin detection

The establishment of maximum permissible mycotoxin limits requires the implementation of highly accurate and reliable analytical techniques (**Pereira *et al*., 2014**).

Chromatography remains the predominant method for detecting and quantifying mycotoxins in food and animal feed due to its high sensitivity and specificity (**Alshannaq *et al*., 2017**). Chromatographic techniques allow both qualitative and quantitative determinations; however, they present certain limitations, including the necessity for extensive sample preparation, prolonged analysis times, specialized expertise, high operational costs, and challenges in data interpretation (**Soares *et al*., 2018).**

The detection of mycotoxins is further complicated by their typically low concentrations, the co-occurrence of multiple mycotoxins within the same food matrix, and the structural variability among different mycotoxins, which collectively hinder chromatographic identification (**Stroka *et al*., 2016**). Among chromatographic methods, thin-layer chromatography (TLC) remains one of the earliest techniques used for rapid screening. Although it is a cost-effective approach, TLC exhibits limitations in terms of precision and sensitivity (**Lin *et al*., 1998**).

Sample preparation is a critical step in chromatographic analysis, as the physicochemical properties of each mycotoxin dictate the appropriate purification and extraction procedures (**Eskilsson *et al*., 2000**). In TLC, the stationary phase typically composed of alumina, silica, or cellulose is immobilized on an inert support such as plastic or glass, forming a matrix for separation. The mobile phase, usually a mixture of methanol, acetonitrile, and water, facilitates sample migration across the stationary phase, allowing for the differentiation and identification of mycotoxin. Due to the simultaneous presence of multiple mycotoxins within the same matrix, analytical methods for their concurrent detection have been recently developed and presented in **Figure 10.**

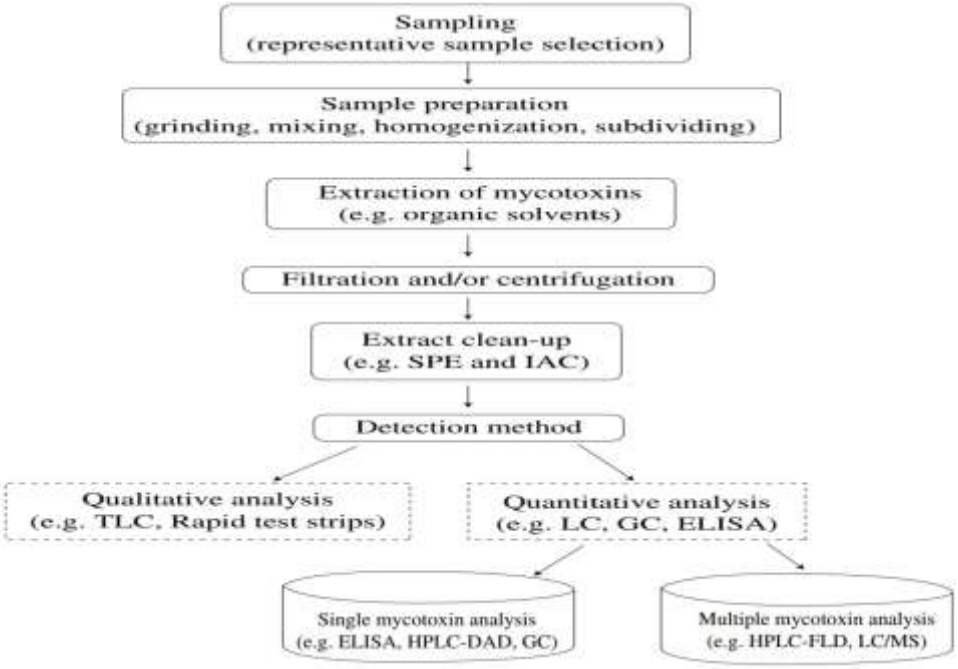

Figure 10 : Flaw diagram of common steps involved in mycotoxins analysis in food

(Alshannak *et al*., 2017).

Research conducted across various countries has highlighted the presence of mycotoxins in plant-derived products, with differences in detection and quantification limits.

In India, an analysis of 63 herb and plant-based product samples detected multiple mycotoxins, including AFB1, AFB2, AFG1, AFG2, and CIT. The study reported a detection limit (LOD) of 10 ng/mL for AFB1, though LOD values for other mycotoxins were not provided (**Aiko *et al*., 2016**). Similarly, a study in Nigeria examined 210 samples of plant-based medicines, identifying AFB1, AFB2, AFG1, and AFG2. However, this research did not specify the LOD or quantification limits (LOQ) **(Ezekwesili-Ofili *et al*., 2014)**.

In Brazil, an investigation of 67 Brazil nut samples detected AFB1, AFB2, AFG1, and AFG2. While the LOD was not specified, the LOQ was reported as 2 mg/kg (**Andrade *et al*., 2013**). In Saudi Arabia, a study analyzing five samples, including almonds, cashews, chestnuts,hazelnuts, pistachios, and walnuts, detected a broad spectrum of mycotoxins. The reported LOD values varied depending on the toxin, with a notable LOD of 5 µg/kg for AFBs (**Abdel-Gawad *et al*., 1993**).

A study in Pakistan analyzed 30 medicinal plant samples, detecting AFB1, AFB2, AFG1, AFG2, and OTA. However, the detection and quantification limits were not specified (**Ahmed *et***

***al*., 2014**). Additionally, a Brazilian study that examined 208 maize-based food product samples found AFB1, AFB2, AFG1, and AFG2, with a LOQ of 2 µg/kg, although the LOD were not reported (**Caldas *et al*., 2007**). **Table 4** provides an overview of the samples, their sources, the mycotoxins detected, and the associated LOD and LO

Table 4. samples, origin, mycotoxins and their LOD, LOQ.

Sample	Origin	Number of Sample	Mycotoxins	LOD	LOQ	Reference
Herbs and Herbs product	India	63	AFB1, AFB2 AFG1, AFG2 CIT	10ng/ml for AFB1 NA for others	NA	**Aiko *et al* .(2016**)
Herbal medicines	Nigeria	210	AFB1, AFB2 AFG1, AFG2	NA	NA	**Ezekwesili-Ofili *et al.* (2014)**
Brazil nuts	Brazil	67	AFB1, AFB2 AFG1,AFG2	NA	2mg/Kg	**Andrade *et al.*(2013)**
Almonds, Cashew nuts Chest nuts Hazelnuts, Pistachio nuts walnuts	Saudia Arabia	5	AFB1, AFB2 AFG1,AFG2, CIT, OTs PAT, T2 ZEA, ST DAS	NA	5µg/kg for AFs NA for others	**Abdel-Gawad *et al*.(1993)**
Medicinal plants	Pakistan	30	AFB1 AFB2 AFG1 AFG2 OTA	NA	NA	**Ahmed *et al*.(2014**)
Corn-based Food product	Brazil	208	AFB1 AFB2 AFG1 AFG2	NA	2µ/kg	**Caldas *et al* .(2007**)

NA not available in the publication **,ST**sterigmatocystin **, DAS** diacetoxyscripenol**.**

Gas chromatography (GC) is seldom used for mycotoxin analysis due to the non-volatile and highly polar nature of these compounds. To enable their detection, a derivatization step is required to convert them into volatile derivatives, typically achieved through silylation or acylation following sample cleanup (**Pereira *et al*., 2014; Alshannaq *et al*., 2017; Zhang *et al*., 2018**). GC operates by differentially partitioning analytes between the stationary and mobile phases within a GC column, ultimately separating and detecting volatile compounds. Among GC detectors, mass spectrometry (MS) is the most widely employed technique, though ion trap and quadrupole analyzers have also been utilized (**Pereira *et al*., 2014**). Time-of-flight (TOF) mass

spectrometry has been applied in the analysis of *Fusarium* toxins in wheat, while triple quadrupole (QqQ) mass spectrometry has been used for detecting *Fusarium* toxins, aflatoxins, and zearalenone in wheat semolina (**Jelen *et al*., 2008**; **Rodriguez-Carrasco *et al*., 2012**). The choice of analytical technique depends primarily on the specific nature of the target mycotoxins **(Soares *et al*., 2018).**

High-performance liquid chromatography (HPLC) remains a widely used technique due to its high resolution and automation capabilities (**Guo *et al*., 2019**). Conventional detectors for HPLC include fluorescence (FLD), ultraviolet-visible (UV), photodiode array (PDA), and MS, either as a standalone detector or in tandem mode (MS/MS) (**Valenta *et al*., 1998**). HPLC-FLD or HPLC-UV can be employed to detect structurally related mycotoxins (**Zhang *et al*., 2018**). In particular, HPLC-FLD is frequently used for ochratoxin A (OTA) quantification due to the compound's natural fluorescence, allowing for a reliable and highly sensitive single-step analysis (**Valenta *et al*., 1998; Lai *et al*., 2015**). However, mycotoxins such as fumonisins (FB) require a derivatization step, as they lack chromophores and do not exhibit natural fluorescence (**Razzazi-Fazely *et al*., 2002**). Several studies have demonstrated the efficiency of HPLC-FLD for detecting AFs, ZEA, and DON (**Valenta *et al*., 1998**). Additionally, HPLC-PDA has been utilized for OT detection, while HPLC-PDA-FLD systems have enabled the simultaneous determination of AFs, ZEA, and DON (**Pascale *et al*., 2019**)

Given the complexity of agricultural matrices and the frequent co-occurrence of multiple mycotoxins, the scientific community has developed more advanced methods for simultaneous detection (**Pascale *et al*., 2019**). Liquid chromatography-tandem mass spectrometry (LC-MS/MS) has emerged as the most powerful and widely used technique for mycotoxin analysis, providing superior accuracy and sensitivity compared to traditional HPLC (**Al-Taher *et al*., 2017; Bessaire *et al*., 2019; Woo *et al*., 2019**). This approach enables the precise quantification of multiple mycotoxins with diverse chemical structures in a single analytical run (**Delmulle*et al*., 2006; Spanjer *et al*., 2008; Zhang *et al*., 2018**), making it the preferred method for mycotoxin surveillance in food and feed.

Among the various analytical techniques available, the European Committee for Standardization (CEN) is actively working to establish standardized methods for mycotoxin analysis. CEN defines performance criteria for these methods, often based on collaborative studies, to ensure reliability and reproducibility. As official reference methods, they are utilized for regulatory control, surveillance, and dispute resolution. Currently, CEN-approved

methodologies exist for detecting mycotoxins in a wide range of food products (**Gilbert & Anklam, 2000**).

II.2. Rapid diagnostic methods for the detection of mycotoxin

The increasing demand for food safety has driven the development of rapid diagnostic methods for mycotoxin detection. These innovative tools enable real-time screening of multiple mycotoxin types with adequate sensitivity and specificity. Their implementation not only enhances food safety monitoring but also reduces production costs and shortens testing durations within the food industry.

This section explores the primary categories of rapid tests currently available, examining their advantages, limitations, and their role in mitigating the risks associated with fungal contamination (**Shephard *et al.*, 2011**).

II.2.1. Immunoassay-Based methods

Rapid diagnostic methods for mycotoxin detection primarily rely on immunochemical assays, including enzyme-linked immunosorbent assays (ELISA), test strips, flow membrane assays, and lateral flow devices (LFDs). Among these, ELISA is particularly significant as it provides a rapid and reliable approach for both the detection and quantification of mycotoxins (**Alshannaq *et al.*, 2017**).

This technique is based on the specific interaction between antigen-antibody complexes and chromogenic substrates, generating a colorimetric response that can be quantified using spectrophotometric analysis (**Pereira *et al.*, 2014**). The high sensitivity, cost-effectiveness, and ease of use of ELISA make it one of the most widely adopted immunoassay methods in mycotoxin screening.

ELISA techniques have been developed for detecting various mycotoxins, including AFs, ZEA, OTA, DON, T-2/HT-2 toxins, and fumonisins (FB) in different agricultural products (**Ursov *et al.*, 2015; Oplatowska-Stachowiak *et al.*, 2016**). The principle behind test strips is similar to ELISA, utilizing immunoassays based on membrane flow to generate qualitative or semi-quantitative results. However, their commercial sensitivity may be limited, as detection outcomes often approach the detection threshold (**Alshannaq *et al.*, 2017**).

Lateral flow devices (LFDs), also referred to as immunostrips or immunochromatographic strips, serve as rapid screening tools widely employed for on-site immunological testing. These devices operate through capillary migration, where colored or labeled complexes move through a porous membrane, allowing results to be visually interpreted or instrumentally quantified. The analyte migrates via capillary action toward immobilized recognition elements on the membrane surface, facilitating detection. LFDs primarily rely on signal labels to indicate results.

To enhance the sensitivity of LFDs, researchers have introduced advanced materials such as quantum dots and nanomaterials. Magnetic and carbon nanoparticles have also gained interest due to their potential to improve assay performance. However, concerns regarding potential toxicity have limited their widespread application. Nonetheless, studies have reported advancements in functionalization, thermal stability, selectivity, sensitivity, and reproducibility of these techniques (**Yang *et al.*, 2019; Fuber *et al.*, 2019**). Materials such as silica, gold, and carbon-based magnetic nanoparticles (MNPs), as well as carbon nanotubes, have emerged as promising molecular recognition platforms (**Qin *et al.*, 2019**).

Recent advancements in nanomaterial-based immunoassays have significantly improved the sensitivity of mycotoxin detection. In a study by **Qi *et al.* (2019**), carbon-based nanoparticles (CNPs) achieved a LOD of 0.2 µg/kg for AFB1 in rice, which was five times lower than that obtained with gold-based nanoparticles. Similarly, **Tao *et al.* (2019**) reported an LOD of 0.15 µg/kg for OTA, representing a threefold improvement over gold nanorods.

Other investigations have explored the use of monoclonal antibodies, specific antibody fragments (Fabs), and aptamers as potential alternatives to polyclonal antibodies (**Yang *et al.*, 2019**). For instance, **Wu *et al.* (2019**) achieved a sensitivity of 3.6 mg/mL for ZEA by employing fluorescently labeled silica beads. Meanwhile, **Anfossi *et al.* (2018**) reported a sensitivity of 62.5 µg/kg for FB1 detection using quantum dots (CdSe/ZnS) and gold nanoparticles (GNPs). **Table 5** presents several examples of various labels employed for the detection of mycotoxins.

Table 5. Different labels used in mycotoxins detection and their sensitivity.

Label	Mycotoxin	Food Commodity	Sensitivity	References
GNPs	CPA	Rice, Maize	1µg/kg 2.5µg/kg	**Li *et al.(* 2020)**
GNPs	DAS	Rice	50µg/kg	**Jin *et al.(* 2020)**
GNPs	FB1	Cereals	5µg/L	**Ren *et al.*(2015)**
ACNPs	ZEA, T-2 DON	Maize	1µg/kg ,13µg/kg 20µg/kg	**Song *et al.*(2014)**
CdSe/ZnSQDs +GNPs	FUMs	Maize	62.5µg/k	**Anfossi *et al* .(2018)**
CdSe/CdS/ZnS QDs	FB1+FB2	Maize	2.8µg/L	**Di Nardo *et al.(* 2016)**

These findings highlight the potential for achieving increasingly lower detection limits, though performance varies depending on the type of markers and detection platforms utilized. The integration of nanomaterials continues to refine the accuracy and efficiency of rapid mycotoxin detection methods, addressing critical needs in food safety monitoring.

II.2.1.1. Biosensors for mycotoxin detection

Biosensors have emerged as a promising tool for detecting mycotoxins in the food industry, offering rapid, reliable, and highly specific analysis. These devices consist of a biological or bioengineered recognition element capable of detecting specific analytes, which is then coupled with a transducer that converts the biological interaction into a measurable electrical signal. Their advantages include high reproducibility, stability, and accuracy, making them suitable for real-time, on-site testing (**Slaughter *et al*., 2018**).

Recent advancements in biosensor technology have significantly improved their efficacy in mycotoxin detection. **Oliveira *et al*. (2019)** emphasized the potential of biosensors in food safety applications, particularly their ability to rapidly identify contaminants with minimal sample preparation. Depending on the detection principle, biosensors typically employ optical transducers such as surface plasmon resonance (SPR) and fluorescence piezoelectric transducers,

including quartz crystal microbalance (QCM), and electrochemical transducers for signal conversion (**Schulz *et al*., 2019**).

The most commonly used biorecognition elements in biosensors include antibodies, peptides, enzymes, nucleic acids, and whole cells. Additionally, advanced materials such as aptamers and molecularly imprinted polymers (MIPs) have been increasingly utilized to enhance specificity and binding efficiency (**Oliveira *et al*., 2019**). To further improve biosensor sensitivity, metallic nanofibers are often incorporated due to their exceptional physicochemical properties, including a high surface-to-volume ratio and strong resistance to corrosion (**Malekzad *et al*., 2017**). These innovations continue to drive the development of highly sensitive and selective biosensors, reinforcing their role as a key technology in mycotoxin monitoring and food safety assurance. **Table 6** summarizes the different biosensors developed for the detection of specific mycotoxins.

Table 6. Exemple of biosensors used in different mycotoxin detection

Transducer/Technic	Mycotoxin	food commodity	detection limit	References
Piezoelectic/QCM	AFB1	Peanut	0.83ng/KG	**Tang *et al.(* 2018**)
Piezoelectric/Q	OTA	Red wine	0.16ng/ml	**Karczmarczyk*et al.(* 2017)**
Impedimetric EIS	AFB1	Corn	0.05ng/ml	**Yagati*et al.(*2018)**
Optical/SPR	OTA	Coffee	0.05ng/ml	**Rehmat *et al.(*2019)**
Impedmetric/EIS	PAT	Apple juice	2.8ng/L	**Khan *et al.(* 2019)**
Optical/FRET	T-2	Wheat, maize	0.00093ng/mL	**Khan *et al.(* 2018)**
Amperometric/CV/DPV	ZEA	Maize	0.00017ng/mL	**He *et al.(* 2019)**
Impedimetric/EIS	FB1	Maize	2pM	**Chen *et al.(* 2015)**
Potentiometric/DPV	OTA	grapejuice ,red wine	180ng/mL	**Xiang *et al.(*2018)**

The developments of sensors for the quantitative detection of various mycotoxins relevant to food and feed safety is presented in **figure 11**. Biological recognition elements such as antibodies (Abs), molecularly imprinted polymers (Apts) are employed in these sensors.

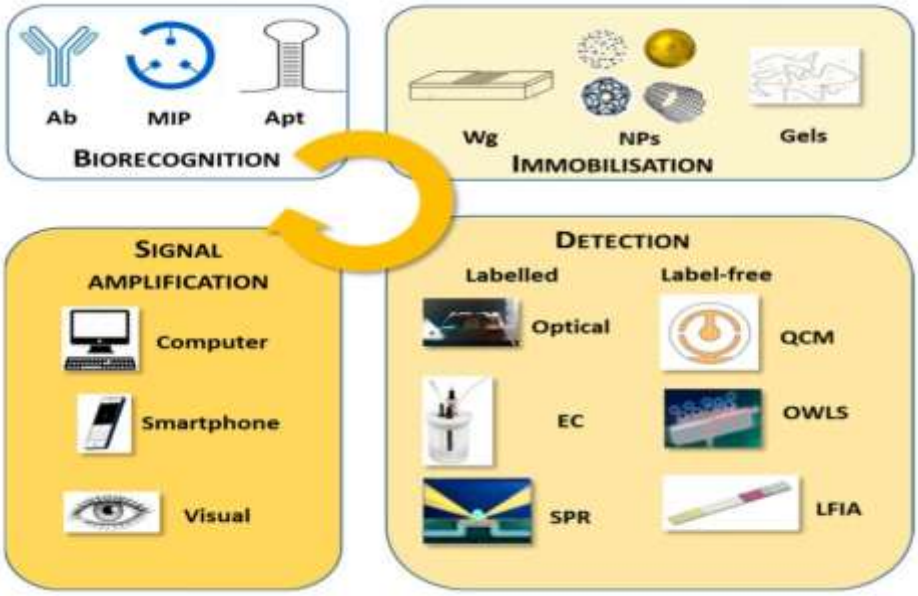

Figure 11 : schematic structures Of biosensor setups with their main functional

units indicated Biorecognition: the element providing molecular recognition and specificity-antibodies (Ab), molecularly Imprinted polymers (MIP), or aptamers (Apt). Immobilisation: surface type the biorecognition element is anchored to-waveguide (Wg), nanoparticles (NP), or gels (Gel). Detection: method of signal generation-electrochemical (EC), optical (Opt), and lateral flow immunoassay (LFIA), as examples using suitable labels for detection, and optical waveguide lightmode spectroscopy (OWLS), quartz crystal microbalance (QCM) And surface Plasmon resonance (SPR), as examples of label-free detection systems. signal amplification: processing the detection signal into a qualitatively or quantitatively assessable, amplified signal **(Krisztina *et al*.,2023).**

II.2.1.1. 1.Electrochemical biosensors for mycotoxin detection

Electrochemical biosensors represent a cutting-edge approach for detecting mycotoxins in food products, leveraging biological recognition elements to generate measurable electrochemical signals upon interaction with target analytes. These devices are particularly valued for their exceptional sensitivity, allowing the detection of mycotoxins at trace levels—an essential capability for food safety assurance.

One of the key advantages of electrochemical biosensors is their high selectivity, as they are designed to specifically recognize target mycotoxins, thereby minimizing false positives and

interference from other food components. Furthermore, these biosensors offer rapid detection, often producing results within minutes, making them well-suited for real-time monitoring in the food industry. Their ability to detect contaminants at early stages enables swift intervention, reducing the risk of mycotoxin exposure and enhancing consumer safety.

Given their precision, speed, and adaptability for on-site testing, electrochemical biosensors are emerging as a promising tool for mycotoxin surveillance and food quality control (**Gaudin, 2017**).

II.2.1.1. 2. Impedimetric sensors

Electrochemical impedance spectroscopy (EIS) has been developed as a highly sensitive technique for mycotoxin identification, monitoring changes at the electrode–redox probe interface (**Ram *et al.*, 2016**). Impedimetric biosensors typically comprise three electrodes: a working electrode, a reference electrode, and a counter electrode. These sensors have been successfully employed for the detection of AFB1, AFM1, OTA, and PAT (**Nan *et al.*, 2019**).

Impedimetric biosensors offer significant advantages, including high sensitivity, excellent selectivity, rapid response time, and ease of use. Moreover, miniaturization and portable instrumentation enhance their applicability in field testing. However, challenges such as the complexity of sensor fabrication and the reliance on expensive labeling markers remain significant limitations (**Oliveira *et al.*, 2019**).

II.2.1.1. 3. Potentiometric Sensors

Potentiometric sensors function by detecting variations in circuit potential between the working and reference electrodes (**Perumal *et al.*, 2014**). Various voltammetric techniques, including differential pulse voltammetry (DPV), cyclic voltammetry (CV), and square wave voltammetry (SWV), have been widely applied in mycotoxin analysis (**Xu *et al.*, 2016**).

These sensors have demonstrated effectiveness in detecting several mycotoxins, such as AFB1 in corn powder (**Zhang *et al.*, 2016**), OTA in grape juice and red wine (**Xiang *et al.*, 2018**), PAT in juice (**He *et al.*, 2018**), and ZEN in corn (**He *et al.*, 2019**). Potentiometric biosensors offer notable benefits, including reduced analysis time, enhanced portability through miniaturization, and high sensitivity and selectivity. Additionally, they allow for direct detection without extensive sample preparation. However, their performance can be influenced by

environmental factors such as temperature, pH, immobilization support, and cross-reactivity in immunological assays (**Xiang *et al.*, 2018**). These factors can impact sensitivity and sensor lifespan, posing challenges for long-term reliability.

II.2.1.1. 4.Amperometric Sensors

Amperometric biosensors utilize either a two-electrode (working and reference) or three-electrode (working, reference, and counter) system, measuring electrical currents generated by electroactive species. The use of mediators enhances electron transfer, improving detection efficiency (**Hammond *et al.*, 2016**).

Common electrode materials include inert metals such as platinum (Pt) and gold (Au), as well as carbon-based nanomaterials like carbon nanotubes and graphene. A major challenge associated with amperometric sensors is the need for meticulous regeneration between measurements. To overcome this limitation, disposable printed electrodes have been developed, offering a cost-effective and scalable solution for large-scale applications (**Ferreira *et al.*, 2013**).

Amperometric biosensors have been successfully employed for the detection of HT-2 and T-2 toxins, AFM1 in human urine (**Schulz *et al.*, 2019**), OTA in red wine (**Tang

***et al.*, 2018**), and ZEN in maize-based products (**He *et al.*, 2019**). These sensors provide significant advantages, including high portability and exceptional sensitivity. However, the necessity of resetting the device after each measurement remains a constraint that may limit their practicality (**Vidal *et al.*, 2013**).

II.2.1.2. Optical Biosensors

Among the various optical biosensing techniques, surface plasmon resonance (SPR) stands out due to its high specificity, enhanced sensitivity, and cost-effectiveness. SPR enables real-time, direct detection, providing rapid and precise results. Additionally, this innovative approach allows for label-free detection and simultaneous qualitative and quantitative analysis of multiple contaminants (**Damborsky *et al.*,2016)**.

SPR-based biosensors have been successfully developed for detecting mycotoxins, include DON, ZEN, and T-2 toxin in wheat (**Gu *et al.*, 2019**), OTA in coffee (**Rehmat *et al.*, 2019)**, and AFM1 in milk (**Karzmarczyk *et al.*, 2017**). The advantages of SPR include its high specificity and sensitivity, compact design, and cost efficiency. It facilitates direct, real-time analysis

without the need for additional labeling, making it suitable for on-site applications. However, despite its promising potential, large-scale implementation of SPR technology remains under development (**Oliveira *et al*., 2019**).

II.2.1.3. Piezoelectric Biosensors

Quartz crystal microbalance (QCM)-based biosensors have been extensively studied for their applications in mycotoxin detection and pathogen monitoring. The QCM transducer consists of a gold-plated quartz crystal whose resonance frequency shifts in response to an applied electrical signal. The quartz surface is coated with a specific sensory layer that induces mass changes, leading to characteristic vibrations (**Montagut *et al*., 2011**).

QCM-based biosensors have been effectively employed for detecting AFB1 in products such as peanuts, pistachios, rice, and wheat (**Gu *et al*., 2019**), as well as OTA in red wine (**Karzmarczyk *et al*., 2017**). These biosensors offer notable advantages, including relatively low cost, high sensitivity, and enhanced selectivity. They are reusable, provide real-time detection, and function without requiring labeling or

irradiation, making them well-suited for integration into portable devices. However, their performance may be affected by background signal interference, which can compromise detection accuracy.

II.3. Emerging Technologies in Mycotoxin Analysis and Detection

The continuous development of innovative technologies for mycotoxin analysis and detection presents promising opportunities to enhance food and environmental safety. These advancements improve accuracy in mycotoxin identification, streamline detection processes, and ensure faster responses in urgent situations. Moreover, emerging technologies offer superior sensitivity, enabling more rigorous monitoring and reducing the risk of contamination. By integrating these advantages, they play a crucial role in safeguarding public health and protecting global food resources (**Smith & Lee, 2023**).

II.3.1. Proteomic and Genomic Methods

II.3.1.1. Proteomic Methods

Proteomic approaches involve the extraction of peptides and proteins from food matrices, followed by in-depth analysis using matrix-assisted laser desorption/ionization time-of-flight

mass spectrometry (MALDI-TOF MS). This technique enables the rapid and highly precise identification of fungal isolates and mycotoxins by detecting proteins within a mass range of 2 to 20 kDa, based on their mass-to-charge (m/z) values. Microorganisms are identified through unique MS fingerprints, making MALDI-TOF MS a promising tool, particularly for distinguishing closely related filamentous fungal species. However, the need for a publicly accessible database containing internal reference entries has been emphasized. Additionally, the food industry currently perceives this method as costly.

MALDI-TOF MS has been successfully applied for the rapid detection of various mycotoxins, including AFB1, CIT, DON, ZEA, T-2 toxin, and griseofulvin. It has also been utilized for the swift screening of Alternaria mycotoxins, such as alternariol (AOH) and its monomethyl ether derivative (AME) (**Hleba *et al*., 2017**).

II.3.1.2. Genomic Methods

Genomic techniques focus on the extraction and analysis of DNA or RNA from molds in food, followed by detection using methods such as polymerase chain reaction (PCR), quantitative PCR (qPCR), loop-mediated isothermal amplification (LAMP), and reverse transcription PCR (RT-PCR). These techniques enable the identification of fungal isolates but do not allow for precise quantification. Moreover, they do not distinguish specific fungal species but rather detect strains with the potential to produce mycotoxins (**Binvihok *et al*, 2016**).

PCR technology facilitates the in vitro amplification of DNA sequences through a selective and repetitive process requiring primers and Taq DNA polymerase. The combination of real-time sensitivity and specific fluorescent signals in conventional PCR allows qPCR to quantify target DNA sequences accurately. LAMP, in contrast, employs DNA polymerase and four primers to enhance specificity, offering a rapid and efficient alternative for detecting mycotoxin-producing molds. PCR-based techniques have been successfully used to identify OTA-producing fungi (**Hayay *et al.*, 2012**). Additionally, fungal species from the *Fusarium*, Penicillium, and Aspergillus genera have been detected using the same approach. These species have further been analyzed for their association with gene expression linked to disease progression, particularly in the biosynthetic pathways of various mycotoxins (**Rodriguez *et al*., 2015**).

II.3.2. Molecular Techniques

Molecular techniques offer a broad array of tools for the detection and identification of fungi, particularly those with toxigenic potential. Among these, polymerase chain reaction (PCR), fluorescence in situ hybridization (FISH), and DNA barcoding are widely applied (**Binvihok *et al.*, 2016**). Various PCR-based approaches including quantitative PCR (qPCR), reverse transcription PCR (RT-PCR), denaturing gradient gel electrophoresis (PCR-DGGE), and PCR-enzyme-linked immunosorbent assay (PCR-ELISA) have proven effective for analyzing food samples. These techniques allow for the precise identification of fungal contaminants and assessment of their ability to produce mycotoxins.

PCR-DGGE, in particular, enables the analysis of terminal restriction fragment length polymorphism (T-RFLP), facilitating accurate differentiation of toxigenic fungal strains (**El Sheikha *et al.*, 2015**). Additionally, PCR-ELISA has been shown to offer greater sensitivity than conventional PCR methods. Another promising technique is loop-mediated isothermal amplification (LAMP), which has demonstrated efficiency in detecting aflatoxin-producing *Aspergillus* species (**Luo *et al.*, 2012**).

DNA barcoding, which relies on the use of short, standardized DNA sequences, has emerged as a powerful tool for distinguishing closely related fungal species, some of which may produce distinct mycotoxins. This approach significantly enhances the precision of fungal identification, thereby supporting improved surveillance and control of mycotoxin contamination in food systems.

As emphasized by **Bennett *et al.* (1997)**, the effectiveness of PCR-based detection of aflatoxigenic fungi depends on targeting genes that are uniquely present in toxigenic strains. The use of primers specifically designed to amplify genes involved in mycotoxin biosynthesis ensures that only DNA from toxigenic fungi generates a positive PCR signal, while non-toxigenic strains yield no amplification (**Figure 12**).

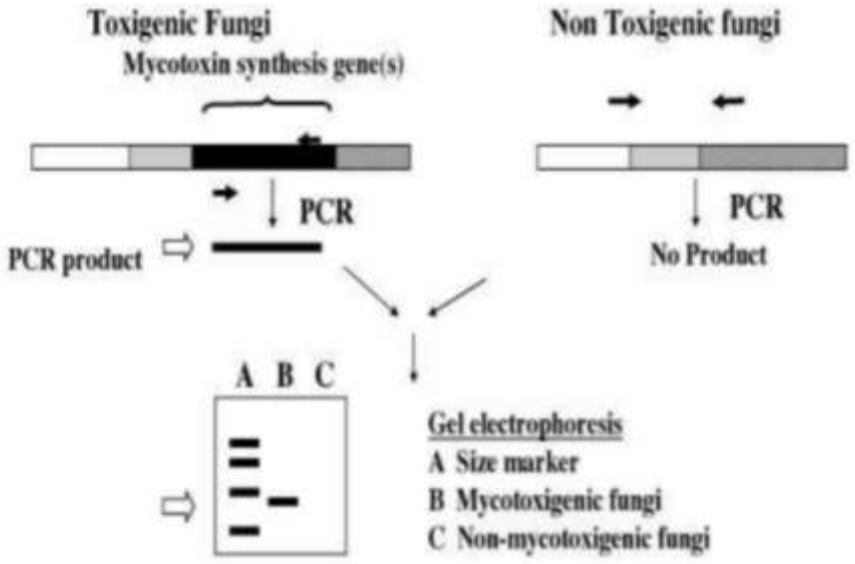

Figure 12 : PCR-based approaches have proven valuable in the detection of mycotoxigenic fungi, as first demonstrated **(Bennett *et al.*, 1997).**

II.3.3. Electronic Nose

The electronic nose is an analytical tool designed to evaluate the physicochemical characteristics of secondary fungal metabolites. It functions similarly to GC by detecting volatile compounds emitted from contaminated food. This detection is performed using a solid-state sensor (**Palascini *et al.*, 2012**). Due to the high sensitivity of the sensors in this method, it is possible to generate a distinct digital fingerprint for each analyzed sample. The detection of characteristic odors provides information about the category of produced metabolites (**Casalinuovo *et al.*, 2006; Sanaeifar *et al.*, 2017**).

The application of this technique has been successful in detecting fungi in fruits such as apples, oranges, strawberries, and peaches, particularly those capable of producing mycotoxins (**Liu *et al.*, 2018; Jia *et al.*, 2019**).

II.3.4. Aggregation-induced emission (AIE) dye

The concept of aggregation-induced emission (AIE) is based on the enhancement of fluorescence intensity observed in specific fluorescent dyes when they aggregate. This increase in fluorescence is primarily attributed to the suppression of intermolecular rotations in the aggregated state. The design of biosensors incorporating AIE technology focuses on evaluating

the fluorescence properties of these dyes (**Liu *et al*., 2014**). **Figure 13** represents principle of aggregation induced emission dye. Several notable AIE dyes are recognized for their strong fluorescence emission in aggregation, including 9,10-distyrylanthracene (DSA), tetraphenylethylene (TPE), methyl silarylate (TPE), and silacyclopentadiene (silole) (**Wang *et al*., 2018**). **Zhu *et al*. (2019)** developed an aptasensor based on AIE dyes for the detection of OTA. These dyes exhibit a high binding affinity for aptamers and fluoresce as a result of aggregation. The study employed a single aptamer sequence, achieving a detection limit of 0.4 ng/mL. Furthermore, the aptamer demonstrated remarkable specificity in identifying OTA.

This approach has been effectively applied for the detection of OTA in wine and coffee, as well as AFB1 in peanuts, oils, and broad bean sauce. The ability to conduct on-site food contamination detection, combined with its user-friendly nature, makes AIE dye-based applications highly efficient.

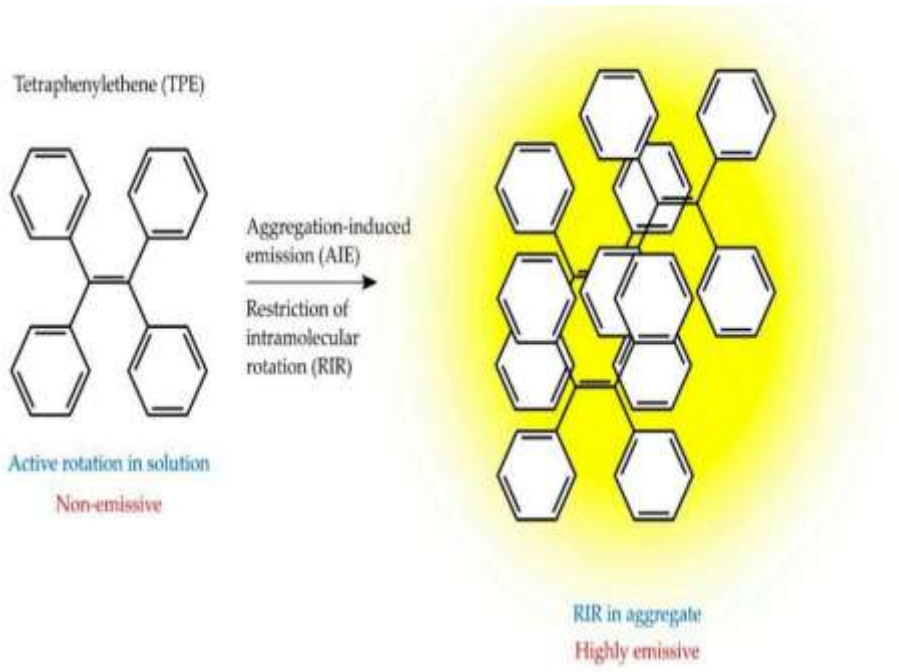

Figure 13 : Principle of aggregation-induced emission **(Zhu et al., 2019).**

II.3.5. Nuclear Magnetic Resonance (NMR) Spectroscopy

Nuclear magnetic resonance (NMR) spectroscopy is a fundamental analytical technique widely employed for identifying organic compounds and studying metabolites **(Xu *et al*., 2014**). This method provides a holistic approach to metabolite analysis, with the most commonly used

NMR methodologies focusing on the physical properties of hydrogen nuclei (protons) in tissues, particularly proton NMR. Additionally, other atomic nuclei such as ^{31}P, ^{13}C, ^{19}F, and ^{23}Na are also subject to analysis.

One of the main limitations of this technique is the restricted access to commercial software and the constraints associated with available quantification methods (**Serkova *et al*., 2012**). Despite these challenges, NMR offers several advantages, including minimal sample preparation, rapid analysis, stable chemical shifts, and the ability to simultaneously measure multiple endogenous metabolites within a living system. In metabolomics, NMR plays a crucial role by providing comprehensive structural insights and enabling the concurrent detection and statistical evaluation of various endogenous metabolites in biological systems.

NMR has also been utilized to investigate the rearrangement process of Fusarium mycotoxins, particularly Fusarin C (**Lopez-Ruiz *et al*., 2019**).

II.3.6. Hyperspectral Imaging (HSI)

Hyperspectral imaging (HSI) is a powerful technique for detecting fungi and mycotoxins, offering notable advantages such as cost-efficient, non-destructive, and rapid analyses while providing detailed spectral data at the pixel level. This method is recognized as a promising alternative to traditional, costly, and time-consuming techniques used for mycotoxin analysis in cereals, significantly improving the detection of contaminated grains (**Femenias *et al*., 2020**).

HSI technology plays a crucial role in assessing the risks associated with Fusarium pathogens and DON contamination. It is particularly useful as a sorting system, enabling the individual classification of contaminated grains.

A complete HSI system consists of a camera for spatial and spectral detection, a

spectrograph for capturing spectral information per pixel, a lens that directs light onto a detector, and an illumination system that projects light onto the sample (**Elmasry *et al*., 2010**). Additionally, it features a mobile unit with a translation stage and motor for sample movement control, along with a data acquisition system (**Elmasry *et al*., 2012**). However, the absence of standardized references presents challenges in reliably identifying metabolites in isolates (**Kleigrewe *et al*.,2012**).**Takle *et al*. (2015**) explored the application of a short-wavelength infrared camera equipped with a mercury telluride detector for detecting Fusarium and DON

contamination in cereal grains, operating within a spectral range of 1000 to 2500 nm. Furthermore, visual hyperspectral imaging (VHI) has been introduced as a potential monitoring technique. In a study by **Barbedo *et al.* (2017**), researchers employed a XENICS camera integrated with a VIS/NIR spectrometer, covering a wavelength range of 528 to 1785 nm. Their objective was to explore the application of HSI in detecting DON contamination in wheat grains using a newly developed algorithm. However, this study failed to establish a conclusive link between DON infection and the presence of Fusarium.

To enhance detection capabilities, an improved algorithm was introduced for batch classification of samples. This novel approach holds promise as an effective tool for identifying early stages of Fusarium infection, which can then be followed by DON analysis for confirmation.

II.4. Comparative analysis of mycotoxins detection technologies

Following the comprehensive overview of individual mycotoxin detection methodologies, a comparative assessment is warranted to evaluate their relative analytical performance and operational applicability. Conventional techniques such as chromatographic and molecular approaches, including HPLC, LC-MS/MS, and PCR-based assays, are characterized by their high sensitivity, specificity, and quantitative accuracy. However, their implementation typically necessitates labor-intensive sample preparation, access to advanced instrumentation, and the involvement of specialized personnel, which can limit their feasibility in low-resource settings or for high-throughput routine screening. In contrast, emerging rapid detection platforms including immunoassays, lateral flow devices, biosensors, and fluorescence-based methods provide advantages in terms of reduced analysis time, user-friendliness, and cost-effectiveness. Despite these benefits, such methods may exhibit constraints related to cross-reactivity, matrix interference, and lower specificity, particularly in complex food and feed samples containing structurally related mycotoxins. To facilitate a critical evaluation of the trade-offs associated with each technique, Table 7 presents a comparative synthesis of the principal mycotoxin detection technologies, summarizing key parameters such as detection limits, specificity, analytical throughput, equipment requirements, and operational complexity. This comparative analysis aims to support the selection of the most appropriate analytical strategy based on the intended application, resource availability, and regulatory demands.

Table 7. Comparative analysis of mycotoxin detection technologies.

Technology type	Suitability across sample materials, conditions, cost considerations	Sensitivity of each method	Reference
TLC	it is a cost-effective method that Allows for the screening of multiple Samples, though it requires prior sample Preparation.	Low sensitivity and poor accuracy	**Yang *et al.* (2014); Singh & Mehta**
LC	For highly polar, non-volatile and thermally unstable MTs	LC-MS/MS provides outstanding selectivity and sensitivity more Reliable analyte identification and enabling the simultaneous detection of multiple mycotoxins	**Yang *et al.*(2020);Pascal *et al.*(2019)**
GC	due to the low volatility and High polarity of the analytes, GCIs not commonly used for the Analysis of MTs. Moreover, Derivatization is required to convert Them into volatile derivatives Some volatile MTs such as TCTC And PAT have been identified and Quantified using (GC) in combination with flame ionization (FID), electron capture (ECD), or MS	the method can be derivatized to produce compounds sufficiently volatile for gas chromatography offering high sensitivity and specificity for MTs	**Alshannaq & Yu. (2017); Pereira *et al.*(2014); Singh & Mehta. (2020)**
ELISA	this method offers a rapid and simple Approach for on -site MTs screeningProviding accurate detection and makingIt highly suitable for routine monitoring Particularly in resource limited settings Compared to chromatographic techniques Such HPLC or TLC, it requires a smaller sample volume, minimal sample preparation and enables high-throughput testing.	cross reactivity (less specificity and sensitivity)	**Al-Jaal*et al.* (2019); Urusov *etal.*(2010); Singh &Mehta(2020); Thway a Salimi-Moosavi .(2014)**
LFIA	it provides rapid results, is cost-effective and well suited for on-site screening Simple Clean-up is often unnecessary and it is commonly employed for the Detection of OTA, ZEN, DON, T-2 toxin And AFs	less sensitive	**Krska & Molinelli.(2009); Gorayacheva *et al.*(2007); Liu *et al* .(2020)**
Biosensors	rapid strips tests allow for simple and low-cost sample analysis, offering Stability and suitability for on-site testing They can potentially be reused, although Some level of sample cleanup is required	optical biosensors are primarily valued for their high sensitivity and capability for real-time Analysis.	**Tudos *et al.*(2003);Pirincci *et al.*(2018);Logrieco *et al* .(2005); Chen &Wang.(2020)**
Electronic –nose	it is capable of detecting a wide range of volatile organic compounds (VOCs)volatile organic compounds (VOCs)OTA in dry-cured pork, FB1 In maize, and DON in wheat bran. Fruits Such as apples, oranges, strawberries, and peaches have been studied, with this Method proving effective in detecting fungi Responsible for mycotoxin production.	unique fingerprint for each food, characteristic each food, characteristic aroma less sensitive to low quantities of MTs	**Camardo *et al.*(2021);Lippolis *et al.* (2016);Ottoboni *et al* (2018); Jia *et al.* (2018) ; Jia *et al.*(2019)**
Infrared spectroscopy	does not require sample preparation	has lower sensitivity than	**Pettersson & Aberg. (2003)**

Flurescent Polarization	it is employed to detect ZEN in corn DON in wheat-based products AFB1 in maize, and OTA in rice	compared to HPLC , the FP method exhibits lower accuracy and sensitivity due to antibody Cross-reactivity with components Of the food matrix	**Zhang *et al* .(2017);Lippolis*et al*.(2006); Zhang *et al*.(2018) Huang *et al*.(2020);Alshannaqn & Yu.(2017**)
Capillarly **electro phoresis**	only limited sample amounts can be analyzed	lacks sensitivity	**Maragos. (1998)**
AIE	the ability to detect food contaminations on-site, combined with the simplicity of operation make AIE dyes highly effective for practical applications.	AIE dyes exhibit high sensitivity and strong affinity for aptamer semitting fluorescence through the mechanism of dye aggregation.	**Zhu *et al* .(2019)**

II.5. Artificial Intelligence and Machine Learning in Mycotoxin Detection

In recent years, artificial intelligence (AI) has rapidly evolved, encompassing various computational techniques that enable machines to analyze data, identify patterns, and make autonomous decisions with minimal human intervention. AI technologies have significantly enhanced food safety by enabling advanced identification and monitoring of mycotoxins in food products and humans (**Zhang *et al*., 2020; Sarker *et al*., 2021; Chakraborty *et al*., 2024).**

These approaches offer numerous advantages, including reliability, cost-effectiveness, and the ability to handle uncertainty **(Chowdhury *et al*., 2012**). Moreover, AI-based techniques can significantly reduce processing times in various analytical applications (**Emri, 2020**). However, the effectiveness of AI in mycotoxin detection depends on the specific task, the accuracy of the models, and the availability of large, high-quality datasets. The development of robust AI models requires comprehensive training using diverse datasets to ensure precise and reproducible results in real-world applications. **Figure 14** illustrates the machine learning process in the form of a block diagram.

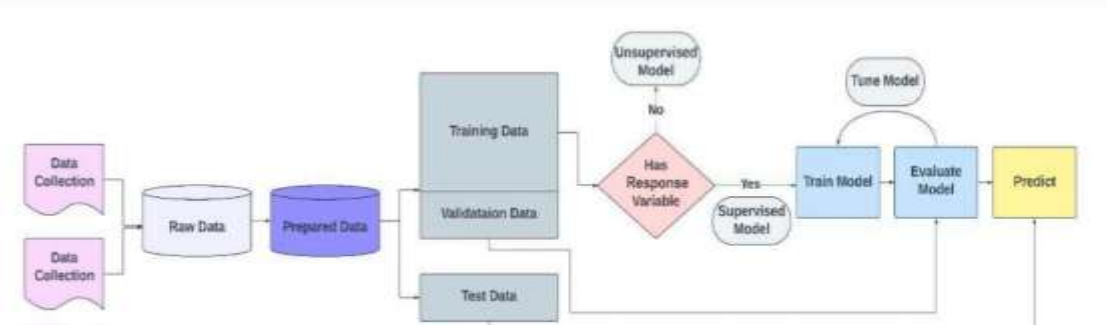

Figure 14 : Block diagram representing the machine learning process

(Inglis *et al* .,2024*)*

II.5.1.Artificial intelligence

Artificial intelligence (AI) is a prominent field within computer science that focuses on developing computational systems capable of performing tasks typically associated with human intelligence (**Ehret *et al*., 2011; Ziyaee *et al*., 2021**). These tasks encompass various cognitive abilities, including reasoning, learning from experience, problem-solving, language comprehension, visual perception, and adapting to changing environments (**Burati *et al*., 2022;**

Resnick *et al.*, 2023). AI technologies are continuously evolving, contributing to advancements across numerous disciplines, including mycotoxin detection and food safety.

Figure 15 and **Figure 16** illustrate the yearly distribution of publications employing machine learning and deep learning technologies for this purpose.

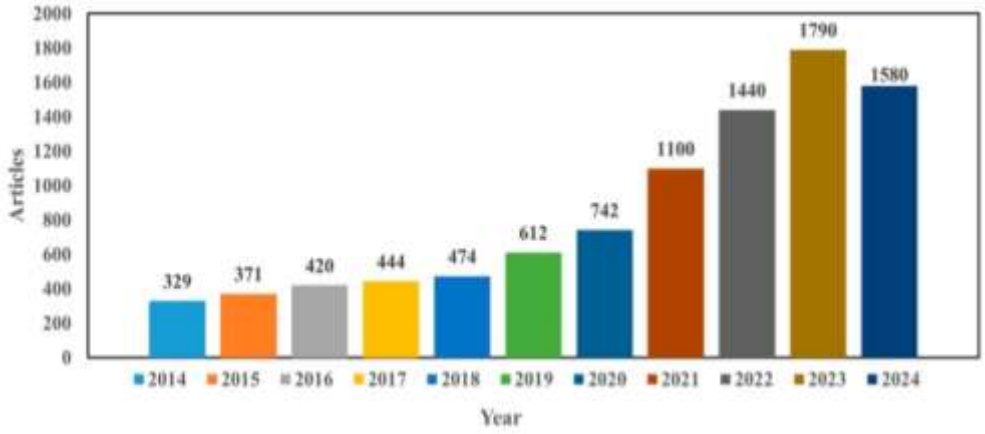

Figure 15 : The number of published articles identified between 2014 and 2024

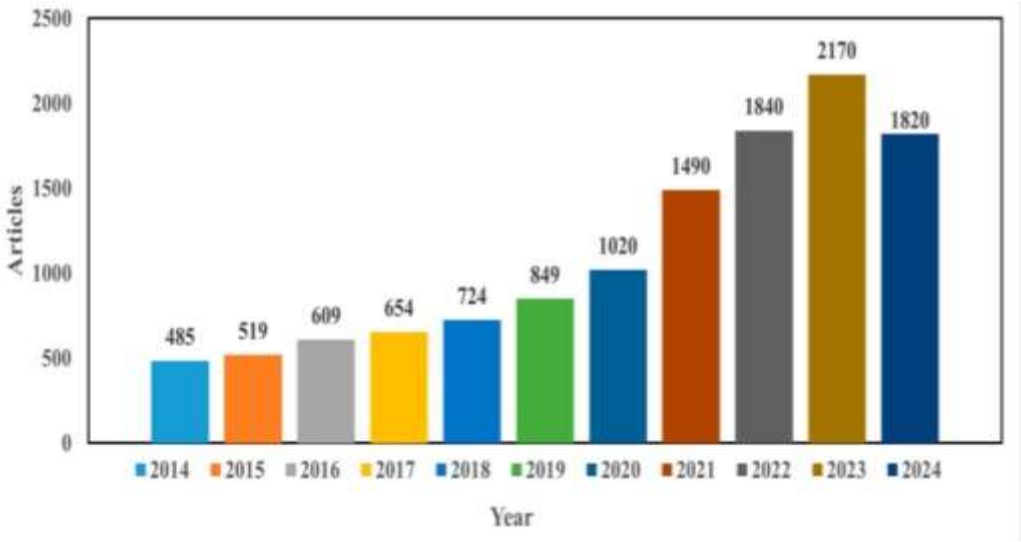

Figure 16 : The number of published articles identified between 2014 and

II.5.2 Machine learning

Machine learning (ML) is a specialized subset of AI that focuses on developing statistical models and algorithms capable of learning from historical data. These models leverage acquired knowledge to perform tasks such as decision-making and predictive analysis without explicit human programming (**Helm, 2021**). ML encompasses several learning paradigms, including

supervised learning, unsupervised learning, and reinforcement learning, each playing a crucial role in data-driven decision-making (**Ullah *et al*., 2020; Varshney *et al*., 2021**).

- **Supervised Learning** involves training models on labeled data, where each input corresponds to a predefined target output. Common algorithms within this category include logistic regression (LR), support vector machines (SVM), random forests (RF), and gradient-boosted regression/classification (**Suhaimi *et al*., 2020; Verma *et al*., 2020**).

- **Unsupervised Learning** enables models to identify patterns in data without explicit labels or predefined guidance. It includes techniques such as clustering algorithms, dimensionality reduction methods, anomaly detection strategies, and association rule learning (**Usama *et al*., 2017; Meena *et al*.,2020; Rajoub *et al*., 2020**).

- **Reinforcement Learning** allows models to learn dynamically by interacting with their environment and adjusting their behavior based on received feedback (**Dong *et al*., 2020**).

The development of machine learning models typically follows five key stages: data collection, data preparation, data splitting, model selection and training, evaluation, and prediction. Among these, validation and test data play critical roles in ensuring model robustness. Validation data, a separate portion of the dataset, are used post-training to prevent over fitting and assess the model's ability to generalize to unseen data. Performance metrics such as mean square error (MSE), accuracy, sensitivity, specificity, and area under the receiver operating characteristic curve (AUC) are commonly used to evaluate model effectiveness and guide further improvements.

II.5.3 Deep Learning

Deep learning (DL) draws inspiration from the way the human brain processes information. This approach leverages vast amounts of data to associate user inputs with corresponding labels, eliminating the need for predefined rules created by humans. DL is built using artificial neural networks (ANNs), where multiple layers process input data from different perspectives. Compared to earlier neural network models, DL significantly enhances accuracy and performance.

DL constructs complex multi-layered models by incorporating transformations and graph-based technologies. It is widely applied in areas such as natural language processing

(NLP), visual data interpretation, and audio and speech processing. Modern deep learning techniques have led to significant performance improvements across various domains (**Adeel *et al.*, 2020; Koppe *et al.*, 2021**). One of the most widely recognized DL architectures is the convolutional neural network (CNN) (**Yao *et al.*, 2019; Dhillon *et al.*, 2019)**. CNNs have gained widespread popularity due to their ability to automatically identify important patterns in data without requiring manual feature extraction, making them highly efficient for complex tasks.

DL is often referred to as a universal learning approach, as it can be applied across various domains. Unlike traditional machine learning models that require manually engineered features, DL models extract optimal traits automatically. Additionally, they exhibit strong adaptability to variations in input data, ensuring consistent performance. This adaptability extends to **transfer learning (TL),** where pre-trained models can be fine-tuned for new tasks, particularly when data is limited. DL architectures such as ResNet have been successfully implemented in high-performance computing environments (**Helm *et al.*, 2021**).

AI techniques, including DL, provide reliable and cost-effective solutions for detecting mycotoxins in food, particularly in peanuts, wheat, and rice (**Chowdhury *et al.*, 2012**).

- **Peanuts:** Machine learning models such as support vector machines (SVM), artificial neural networks (ANNs), and adaptive neuro-fuzzy inference systems (ANFIS) have been used to detect AFB1 with high accuracy. A combination of LED lighting and ANNs achieved 99.7% accuracy in detecting fungal growth (**Ziyaee *et al.*, 2021**). Deep learning models, including CNNs and deep convolutional neural networks (DCNNs), have also been effective in identifying mold contamination (**Manhando *et al.*, 2021**).
- **Wheat:** CNN models analyzing RGB images achieved 97% precision and 99% accuracy in detecting Fusarium head blight (FHB) (**Bernardes *et al.*, 2022**). Transfer learning with DCNNs yielded an average accuracy of 0.92 (**Qiu *et al.*, 2019**). AI-based microwave detection methods have also demonstrated perfect precision, recall, and F1-score (100%) in identifying AFB1 contamination (**Deng *et al.*, 2023**). Additionally, RF models have been employed to detect multiple mycotoxins in wheat, including DON, ZEA, FUMs, AFs, and OTA. Satellite imagery combined with crop phenology data

further enhanced AI-driven detection, achieving internal and external validation accuracies of 99% and 90%, respectively (**Wang *et al.*, 2022**).

- **Rice:** AI models, including SVM, CNN, and deep belief networks (DBN), have been used to identify mold species such as *Aspergillus* and *Penicillium* in stored unhulled paddy. Among these models, DBN has demonstrated the highest accuracy **(Sun *et al.*, 2016**)**..**

III. Mycotoxin Control Strategies: Prevention and Decontamination/Detoxification in Foods

The reduction of mycotoxin contamination in agricultural commodities is a major concern in many countries worldwide, prompting the implementation of various preventive measures **(Misihairabgwi *et al*., 2016)**. Pre-harvest strategies primarily aim to prevent the development of toxigenic fungi and, consequently, the formation of mycotoxins. However, once mycotoxins are produced, their detoxification must rely on post-harvest interventions **(Luo *et al*., 2018).**

Although it is impossible to completely eliminate the risk of mycotoxin contamination, preventive actions can significantly reduce it. Environmental conditions, particularly climate, play a crucial role in mold development and are beyond human control. Nevertheless, plant productivity and stress levels can be managed through several strategies that also contribute to lowering mycotoxin levels. These strategies include the application of Good Agricultural Practices (GAP) to prevent contamination during cultivation, and Good Manufacturing Practices (GMP) to ensure appropriate handling, storage, and processing **(Ji *et al.*, 2014; Adeyeye, 2019).**

Contamination control methods are generally categorized into three stages: pre-harvest, harvest, and post-harvest. If contamination occurs despite these measures, additional interventions may be employed. These include the decontamination of food using physical, chemical, or biological methods, the dilution of contaminated products with uncontaminated ones (subject to local regulations), or the diversion of contaminated commodities to biofuel or biomass production **(Kumar *et al*., 2017).**

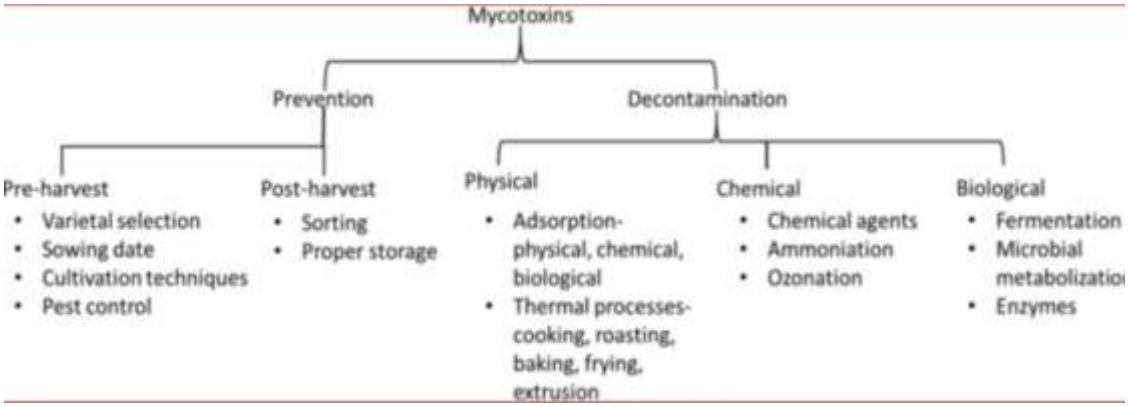

Figure 17 : prevention and decontamination strategies for mycotoxins(Pankaj &Keenes, 2017).

III.1 Pre-Harvest strategies

Preventive strategies targeting mycotoxins prior to harvest include crop selection, optimized sowing time, irrigation management, crop rotation, tillage practices, proper fertilization, and effective pest and weed control **(Awad *et al*., 2010; Hahn *et al*., 2015).**

III.1.1 Crop Selection: Breeding and cultivating resistant or less susceptible crop varieties is one of the most effective approaches for minimizing fungal infection and subsequent mycotoxin production **(Awad *et al*., 2010; Hahn *et al*., 2015).**

III.1.2. Sowing Time: The timing of sowing influences the flowering stage, which is critical because fungal spore release often coincides with flowering. When synchronization occurs, the risk of contamination especially in maize, wheat, and barley increases. Early sowing can significantly reduce this risk **(Munkvold, 2003; Jouany, 2007).**

III.1.3. Irrigation Management: While irrigation alleviates plant stress, it should be carefully managed, particularly during flowering and maturation stages. Excessive moisture during these periods promotes the spread of *Fusarium* species, particularly in wheat, barley, and rye **(Awad *et al*., 2010).**

III.1.4. Crop Rotation: Continuous cultivation of maize or wheat heightens disease risk. Rotating with non-host crops such as rapeseed, sugar beet, sunflower, or soybean can reduce mycotoxin contamination. Schafsma *et al*. **(2001)** demonstrated that rotating with

crops other than wheat over a two-year period significantly reduced DON contamination during subsequent wheat cultivation **(Jouany, 2007; Awad *et al*., 2010).**

III.1.5.Tillage Practices: Deep ploughing (10–30 cm) is more effective than minimal or no-tillage in burying infected residues and reducing the growth of *Fusarium graminearum*, thereby lowering DON contamination **(Jouany, 2007; Awad *et al*., 2010).**

III.1.6. Fertilization: Fertilizer regimes influence fungal contamination by modifying crop residue decomposition, enhancing plant vigor, and altering soil microbial activity **(Awad *et al*., 2010).**

III.1.7. Weed and Pest Control: Weeds serve as reservoirs for pathogenic fungi, and mechanical damage caused by insects or birds facilitates fungal entry into plant tissues **(Teich *et al*., 1984).**

III.1.8. Biological Control Strategies: The application of biological control agents offers a promising approach to reduce fungal growth and mycotoxin production. These include non-toxigenic strains of *Aspergillus flavus* and antagonistic microorganisms such as bacteria, yeasts, and fungi. Notably, *Bacillus subtilis*, *Pseudomonas putida*, and *Streptomyces* spp. produce enzymes like chitinases and antimicrobial metabolites that inhibit fungal pathogens. These biological treatments have demonstrated up to 90% efficacy in both greenhouse and field trials **(Sarkanj *et al*., 2020).**

III.1.9. Use of Atoxigenic and Antagonistic Microorganisms

Deploying non-toxigenic strains of molds, such as *A. flavus*, can outcompete aflatoxigenic strains, thereby reducing aflatoxin accumulation in crops like maize **(Slavic *et al*., 2020).** Other microbial agents suppress *Fusarium* species through mechanisms such as resource competition, inhibition via secondary metabolites, and the induction of plant defense responses before infection. Recent developments include the use of living microbial agents (bacteria, fungi, viruses) and their metabolites as biocontrol tools.

These beneficial microorganisms can inhibit fungal growth and downregulate mycotoxin biosynthesis, offering a sustainable means to safeguard crops. Among them, endophytic microorganisms, which live symbiotically within plant tissues, are particularly promising, as they enhance plant resistance to both abiotic stress and pathogens.

Biological control operates not only through direct antagonism of toxigenic fungi but also via competition for ecological niches, thus reducing conditions favorable to mycotoxin formation.

III.1.10. Biotransformation of Mycotoxins

An emerging area of interest is the biological degradation or transformation of mycotoxins by microbial agents. Although the mechanisms remain under investigation, preliminary research shows promise **(Swanson *et al.*, 1988; Siddiqui *et al.*, 2005).** Strategies include the treatment of crop residues and seeds to suppress fungal populations and the application of microbial inoculants during crop growth to stimulate plant defenses. Post-harvest treatments targeting plant residues can also inhibit further fungal development. These methods are not only effective but also align with environmentally sustainable agricultural practices.

III.1.11.Microbial Antagonism and Antifungal Metabolites

Bacterial strains capable of producing antibiotic-like compounds are especially effective against filamentous fungi. Enzymes such as chitinases break down fungal cell walls, while antimicrobial substances including peptides, polyketides, amino sugars, and phospholipids contribute to fungal inhibition **(Swanson *et al.*, 1988; Schisler *et al.*, 2002)**. Several *Bacillus* species have shown notable potential in suppressing *Fusarium* spp.

In laboratory studies, strains such as *Paenibacillusmacerans*, *Pseudomonas putida*, *Sporobolomyces roseus*, and *Bacillus subtilis* have inhibited *Fusarium graminearum* growth by 95–100% **(Perondi *et al.*, 1996; Stockwell *et al.*, 1997)**. Field and greenhouse trials further demonstrated that culture filtrates from these microbes reduced *Fusarium* contamination by 21–26% **(Luo *et al.*, 1999; Fernando *et al.*, 2001).**

III.2. Harvest Strategies

Harvesting should be carefully timed to coincide with the crop's full maturity and dry weather conditions. This helps to avoid elevated moisture levels that promote the activity of mycotoxins producing molds (**Awad *et al.*, 2010)**. If crops are left in the field beyond ripeness, they are more exposed to pests and insects, their protective outer layer becomes compromised, and they endure prolonged environmental stress. This increases the risk of mycotoxin formation particularly under extended light exposure and can also lead to

mycotoxin modification through binding with sugars, proteins, fats, or integration into starch (**Awad *et al*., 2010; Kovac *et al*., 2018; Kovac *et al*., 2018).**

Post-harvest, cereals must be transported in clean containers to storage facilities such as silos or processing plants. While short-distance transport doesn't allow for mold growth, it can still result in contamination with mold spores. Long-distance transport (e.g., by ship, truck, or train) may contribute to an increase in overall mycotoxin levels.

Clean, well-prepared storage is essential to preserving crop quality. Grain moisture must be reduced below 14% to prevent fungal and bacterial development. Facilities equipped for pre-storage cleaning and sorting can help separate lower-quality grains (typically used for feed) from those intended for human consumption, which should be screened for mycotoxins. If toxin levels exceed legal limits, the contaminated portion must be processed to comply with regulations. This can include dilution, use as animal feed (where higher mycotoxin levels may be permitted), or physical and chemical treatments such as washing, soaking **(Petric *et al*., 2018)**, blanching, malting **(Mastanjevic *et al*., 2018; Spanic *et al*., 2019)** and fermenting **(Habschied *et al*., 2011;Qiuping *et al*., 2019)** or removing the outer shell methods that exploit the chemical properties and localization of mycotoxins within the grain **(Habschied *et al*., 2011)**. Additionally, antifungal or antimycotoxigenic treatments synthetic **(Sarkang *et al*., 2013; Cacic *et al*., 2014)** natural (**Jerkovic *et al*., 2019; Torres *et al*., 2003**) or nanoparticle-based (**Kovac *et al*., 2018; Kovac *et al*., 2020)** can be applied to crops or storage areas to further reduce contamination. Throughout processing and transportation, care should be taken to protect the integrity of the crop's outer shell, which acts as a barrier against mold invasion.

It is important to note that the presence of molds does not always indicate the presence of mycotoxins, and vice versa. Molds may be in an early growth stage or may be non-toxigenic, while crops may still contain residual mycotoxins even if no visible mold is present (**Kovac *et al*., 2018**).

III.3. Post Harvest Strategies

The decontamination or detoxification of mycotoxins in agricultural products presents both scientific and practical global challenges. Several approaches have been proposed, including natural methods (e.g., thermal insulation, irradiation, low-temperature plasma), chemical techniques (oxidation, reduction, hydrolysis, alcoholysis, adsorption), and biological

interventions using microbial agents **(Lyagin *et al.*, 2019).** While chemical and physical treatments often suffer from limitations such as nutrient loss, inefficiency, high costs, and the requirement for specialized equipment, biological methods are generally considered more effective, targeted, and environmentally sustainable **(Wang *et al.*, 2019).**

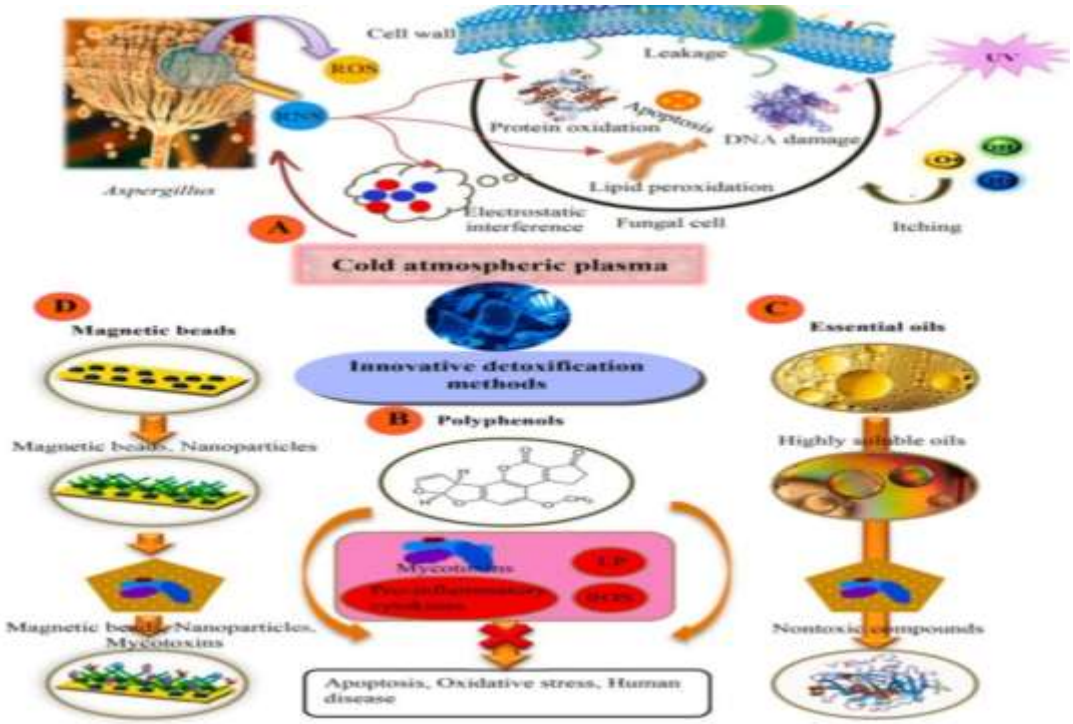

Figure 18 : Methods for controlling mycotoxins contamination (A) cold atmospheric plasma method, (B) polyphenols, (C)Natural essential oils , and (D) magnetic materials and nanoparticles **(Sanzani *et al.*,2009 ; Tian *et al.*,2011 ; Wu *et al.*,2020 ; Cai *et al.*,2022).**

III.3.1. Physical Treatments

Physical methods for reducing mycotoxin levels include sorting, grading, removal of visibly affected portions, drying, cleaning, segregation, milling, boiling, roasting, irradiation, extrusion, microwave heating, and peeling. Incorporating these techniques into post-harvest Hazard Analysis and Critical Control Point (HACCP) systems can significantly mitigate contamination risks **(Sarrocco *et al.*, 2018 ; Shi *et al.*, 2018).**

III.3.1. 1.Sorting

Sorting and cleaning serve as the first line of defense against mycotoxin contamination. These non-invasive techniques have proven effective; for instance, sorting can reduce patulin levels in fruit products by up to 99% **(Luo *et al.*, 2018)** and FB1 levels in maize by 26–93%.

Aflatoxins (AFs), which are typically unevenly distributed, can be significantly reduced by discarding visibly damaged kernels. Additionally, ultraviolet light has shown promise in screening contaminated cereal batches **(Stryken, 2003).**

III.3.1. 2.Processing

Although processing cannot completely eliminate mycotoxins, it can significantly reduce their concentrations **(Stryken, 2003)**. Mycotoxins such as DON and ZEN, often located on grain surfaces, can be partially removed through surface treatments like peeling. While many mycotoxins are heat-resistant, some degrade at elevated temperatures; for example, extrusion at 150–200 °C has been reported to reduce AFB1 by up to 79%, especially under humid conditions **(Shi *et al*., 2014).**

III.3.1. 3.Storage

Storage conditions greatly influence fungal development and subsequent mycotoxin production. Key factors include temperature and humidity. Optimal storage practices—such as temperature control, ventilation, adequate packaging, and moisture regulation—are essential to limit both fungal proliferation and mycotoxin accumulation. Poor storage is a major contributor to post-harvest losses, particularly in developing countries, where such losses can reach 20–50% **(Iqbal *et al*., 2021).**

III.3.1.4.radiation-Based and Pulsed Light Treatments

Radiation-based technologies, including both ionizing (e.g., gamma rays, electron beams) and non-ionizing radiation (e.g., pulsed light), are promising physical methods for reducing fungal pathogens and degrading mycotoxins in food products. Ionizing irradiation has been shown to reduce mycotoxins such as ZEA, OTA, and AFB1 by over 90% in some instances, with gamma and electron beam treatments considered safe up to 10 kGy **(Kalagatur *et al*., 2018)**. However, potential alterations in food structure and quality demand careful, controlled application **(Sipos *et al.*, 2021).** Pulsed light treatment, another innovative and cost-effective approach, does not leave residues on treated commodities and primarily disinfects surfaces and reduces seed germination **(Mir *et al*., 2021)**. Its effectiveness depends on factors related to the food matrix (type, thickness, composition), the mycotoxin (type), and light parameters (pulse energy, number of pulses, and distance). For example, Wang *et al.* **(2016)** reported a 75% reduction of AFB1 and AFB2 in rice treated with 0.52 J/cm² per pulse

for 80 seconds, while Chen *et al*. **(2019)** observed a 35.5% reduction in DON in grains treated with 180 pulses over 60 seconds. Additionally, combining pulsed light with citric acid has enhanced AFs degradation in peanuts **(Abuagela *et al*., 2019).** Nonetheless, limited penetration depth remains a major drawback, restricting its use mainly to surface decontamination of solid foods, particularly those unpackaged or packed in UV-transparent materials. Despite their potential, both irradiation and pulsed light treatments present limitations, including lipid and protein oxidation, discoloration, and changes in organoleptic properties, which may hinder their broader application in the food industry **(Olatunde *et al*., 2021).**

III.3.1. 5.Cold Atmospheric Plasma (CAP)

Cold Atmospheric Plasma (CAP) is a non-thermal state of matter generated by applying an electric field to a neutral gas, resulting in partial ionization of the gas into plasma. When the applied voltage exceeds the gas's breakdown threshold, various reactive oxygen and nitrogen species (RONS) are produced, including atomic oxygen (O), ozone (O3), hydrogen peroxide (H2O2), hydroxyl radicals (·OH), peroxynitrite ($ONOO^-$), nitrite (NO_2^-), nitrate (NO_3^-), as well as ultraviolet (UV) radiation and electrical discharges **(Esua *et al*., 2021; Ali *et al*., 2022).** These reactive species are generated at room temperature and atmospheric pressure, making CAP a promising tool for decontamination applications.

CAP is used by exposing water, buffer solutions, or acidic media to plasma discharge, generating potent sanitizing agents for cleaning and disinfection **(Ali *et al*., 2022).** Its antimicrobial activity and ability to degrade complex biochemical compounds stem from the synergistic effects of the aforementioned reactive species and UV light. As a non-thermal process, CAP maintains temperatures close to ambient, preserving the quality of treated materials. The choice of working gas (e.g., air, nitrogen, oxygen) is crucial, as it influences the type and abundance of reactive species, which should be tailored to the intended application, such as microbial inactivation or mycotoxin detoxification.

Chen *et al*. (2017) found that treating samples with atmospheric air plasma at 50 kV for 8 minutes led to a 25.82% reduction in DON, with treatment efficacy enhanced by increasing moisture content from 8% to 20%, resulting in a 36.10% improvement. Similarly, in oat meal, the reduction of T-2 and HT-2 toxins was significantly influenced by factors such as relative humidity, treatment duration, and the gas type used. **Kis *et al*. (2020)** showed that nitrogen

(N2)-based CAP oxidized samples efficiently, reducing T-2 and HT-2 toxins by 42.24% and 37.53%, respectively. **Wang *et al*. (2022)** demonstrated that increasing the voltage from 10 to 30 kV decreased levels of alternariol and alternariol monomethyl ether in jujube extract by 1.3%–56.5%.

Corona discharge plasma was also shown to reduce AFB1 in rice and wheat by 45–56% within 30 minutes **(Paligundla *et al*., 2020),** possibly due to the disruption of the C8–C9 double bond in the furofuran ring and alterations in lactone, cyclopentanone, and methoxyl groups. CAP has also outperformed gamma irradiation in detoxifying hazelnuts, reducing AFB1 by 70–73% and AFB2 by 15–47%, with minimal effects on sensory properties. **Wielogorska *et al*. (2019)** reported that CAP-induced mycotoxin degradation followed first-order kinetics, with half-lives of 1.1 minutes for enniatin B and 74 minutes for DON. A 10-minute treatment reduced FB1 and AFB1 levels by 64% and 65%, respectively, with no notable cytotoxicity from the resulting degradation products.

The mechanisms underlying CAP-mediated mycotoxin degradation involve oxidative reactions driven by species such as ozone, hydroxyl radicals, and UV photons. These agents penetrate fungal cells, damaging membranes, causing cytoplasmic leakage, and ultimately leading to cell death **(Misra *et al*., 2019)**. CAP also disrupts DNA and protein structures, triggering apoptosis and spore contraction **(Chen *et al*., 2022).** For example, Gavahian and **Cullen (2020)** reported that plasma-induced reactivity compromises fungal cell wall integrity. **Lee *et al*. (2015)** showed that plasma exposure alters the structural properties of *Cordyceps bassiana* spores, leading to their inactivation.

As an eco-friendly, rapid, and effective technology, CAP shows strong potential for antimicrobial and antimycotoxigenic applications. However, further studies are needed to assess long-term safety and the nature of any secondary by-products **(Hojnik *et al*., 2017; Ten *et al*., 2017; Mir *et al*., 2021).** Wielogorska *et al*. **(2019a)** demonstrated a 65% reduction in AFB1 and FB1 in maize after 10 minutes of CAP treatment at 20 Hz. Mravlje *et al*. **(2021)** also reported a significant decline in *Alternaria* and *Epicoccum* species in buckwheat following 90–120 seconds of CAP exposure. Ott *et al*. **(2021)** observed over 99% DON degradation and a >80% improvement in Caco-2 cell viability following 20-minute air-based CAP treatment of 100 µg DON in liquid suspension. However, the same treatment applied to powdered DON reduced the toxin by only 33%, with a modest impact on cell viability.

Chen *et al*. (2022) concluded that an 8-minute air CAP treatment at 50 kV achieved 83.99% degradation of DON in wheat, with minimal effects on overall grain quality, aside from a slight decrease in flour whiteness.

III.3.1. 6.Pulsed electric fields

Pulsed electric fields (PEFs) have emerged as a promising non-thermal technology for controlling *Aspergillus flavus* contamination and reducing the associated production of AFB1 and AFG1 **(Gavahian *et al*., 2020).** This technique has shown effectiveness in neutralizing mycotoxins present in food matrices. However, food-specific assessments are essential before implementing PEFs on an industrial scale to ensure product quality and safety.

Similarly, microwave-based thermal treatments (WMTs) have been evaluated for their potential to degrade mycotoxins**. Zhang *et al*. (2020)** demonstrated that WMTs significantly reduced AFB1 levels in maize without causing thermal damage to the kernels, highlighting the viability of microwave methods for AFs reduction in cereal grains. In contrast, high-pressure processing (HPP) has shown efficacy in reducing mycotoxin content in fruit juices. Gavahian and Cullen **(2020)** also underlined the potential role of active packaging technologies in inhibiting the growth of harmful molds and reducing mycotoxin accumulation in a wide array of products, including fruits, vegetables, nuts, bakery goods, and dairy products.

Additionally, biopolymers such as proteins and lipids have attracted interest for their mycotoxin-binding capacities due to their low cost, environmental sustainability, and compostability. Among chemical approaches, nano-structured adsorbents, especially those based on bentonite clays, are being investigated for OTA removal from food items such as cheese. **Hamad *et al*. (2021)** assessed the detoxification efficiency of calcium and sodium bentonites both in vitro and in vivo. Calcium bentonite demonstrated superior adsorption capacity in phosphate-buffered saline (PBS) compared to sodium bentonite. In vivo studies in rats indicated no adverse enzymatic activity upon co-administration of OTA and bentonite, unlike the effects observed with OTA alone. Structural analysis using scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR) confirmed the efficacy of bentonites as OTA-binding agents. Furthermore, the incorporation of calcium bentonite into feta cheese not only facilitated OTA removal but also enhanced the product's sensory attributes, supporting its use as a food-safe detoxifying agent **(Hamad *et al*., 2021).**

Table 8. represent physical treatment for mycotoxin and their advantage and limitation

Physical Method	Principle	Target Mycotoxins	Effectiveness	Advantages	Limitations
Sorting And Sieving	Mechanical Removal Of Moldy Or Damaged Grains	Afs, FB1	40–80%	Low-Cost, Simple, Scalable	Does Not Remove Invisible Or Internal Contamination
Thermal Processing	Heat Degrades Or Reduces Some Mycotoxins (Drying, Roasting, Boiling)	Zea, Ota	10–70%	Easy To Apply With Existing Infrastructure	Afs And Some Trichothecenes Are Heat-Resistant
Irradiation (UV, Gamma)	Mycotoxin Breakdown By Ionizing Or UV Radiation	Afs, PAT OTA	50–90%	Non-Thermal, Leaves No Residue	Regulatory Limits, Expensive, Can Affect Food Quality
High Pressure Processing	Inactivates Contaminants Using High Hydrostatic Pressure (>400 Mpa)	Afs, Fb1	30–70%	Preserves Nutrients And Taste	High Equipment Costs, Not Widely Accessible
Cold Plasma Treatment	Reactive Species (O3, No, Radicals) And Uv Break Down Mycotoxins	Afs, Ota, Don	60–100%	Rapid, Energy-Efficient, No Chemicals	Still Under Development, Industrial Scaling Limited
Physical Adsorption	Uses Membranes Or Filters To Trap Or Separate Mycotoxins Fromliquids	Various (Especially In Liquids)	30–90%	Useful In Liquid Foods Or Beverages	Not Applicable To Solids; Filter Fouling Possible

III.3.2. Chemical control bases (Ammonia, Hydrated Oxide)

Ammonia treatment of seeds has been shown to reduce various mycotoxins (AFs, FBs, OTs) to undetectable levels, while inhibiting the growth of mycotoxigenic <fungi. However, this method is prohibited in the EU for food intended for human consumption. The combination of glycerol and calcium hydroxide has also been found effective in detoxifying mycotoxins **(Luo *et al.*,2018).** Sodium hydroxide and potassium hydroxide are commonly used to degrade AFB1 in contaminated soils, but they can lead to secondary contamination and negatively affect the nutritional quality of the products (**Sipos *et al.*,2021)**.

III.3.2.1.Chitosan

Chitosan , a linear polysaccharide second only to cellulose in abundance in nature, possesses antifungal, antibacterial, and antiviral properties. These traits make it an attractive option for

food preservation **(Grande-Tovar *et al.*, 2018; Zachett *et al.*, 2019).** The combined use of chitosan and water activity (aw) has been shown to control fungal growth and mycotoxin production, particularly by Fusarium species (*F. proliferatum*, *F. graminearum*, and *F. verticillioides*) in maize and wheat. In experiments with irradiated grains, low-molecular-weight chitosan (with >70% deacetylation) reduced DON and FB production when applied at a dose of 0.5 mg/g. Additionally, the use of 1% chitosan enriched with 1% lemon essential oils reduced DON levels in figs, while *Ascophyllumnodosum*, a marine brown alga, also decreased DON in wheat grains (**Gunupuru *et al*.,2019).**

III.3.2. 2.Ozone Treatment

Ozone (O3) has been extensively studied for its ability to degrade mycotoxins. It is a simple technology that leaves no harmful residues after use (**Soares *et al.*, 2020**) and is applied to disinfect cereals, vegetables, and fruits, or to detoxify mycotoxins **(Zhuang *et al.*, 2020).** Research shows that ozone is particularly effective at degrading AFs, especially AFB1 and AFG1, due to the C8–C9 double bond in their structures, with AFG1 being the most sensitive. Under optimal conditions (55 g $O_3 \cdot h^{-1}$ for 6 hours), ozone treatment resulted in a significant decrease in DON (29%-32%) (**Li *et al.*, 2019)** and its modified form, DON-3-glucoside (44%). Ozone treatment also led to a marked microbial decline in durum wheat, without affecting the chemical and rheological properties of semolina and pasta made from ozonated wheat. Furthermore, ozone treatment transformed DON into various ozonized products, and the degradation rate of DON was positively correlated with ozone concentration and treatment time. Specifically, a 30-second treatment at 1 $mg \cdot L^{-1}$ ozone concentration achieved a 54.2% degradation rate. The moisture content of the wheat granules also significantly impacted the degradation rate, with 57.3% degradation achieved when applying 60 $mg \cdot L^{-1}$ ozone for 12hours at 17% moisture content. Research also indicated that fresh noodles made from ozone-treated wheat flour showed increased resistance to microbial growth.

III.3.3. Biological Control

Over the past two decades, diverse research teams have identified numerous microorganisms capable of detoxifying mycotoxins in food and feed. Biological methods offer an eco-friendly alternative to chemical and physical treatments, often yielding fewer or non-toxic by-products. Both pure microbial strains and fermentation processes have

demonstrated strong in vitro efficacy in degrading or binding mycotoxins **(Wang *et al.*, 2019**).

III.3.3.1. Detoxification by microorganism

Numerous thinks about have centered on the mycotoxin detoxification capacities of microorganisms, but a stronger understanding of capable chemicals and the instruments included is still required. In a few particular case, no coming about metabolites were identified after mycopoison biodegradation caused by microorganisms, but generally, one or different compounds are ordinarily recognized. Table 9 gives an outline of mycotoxins corruption caused by microorganisms with a center on the included chemicals, corruption responses, and coming about metabolites **(Ndiaye *et al.*, 2022).**

Table 9. detoxification mycotoxins by microorganism

Microorganisme	Gene orenzymes	Toxins	degradation reactions	obtained metabolites	References
Tetragenococcus	Enzyme	AFB1	adsorption+enzymatiqual action	C14H10O4,C18H16O8,	**Li *et al.*(2018)**
Halophilus	ND*			C14H12O3,C16H20O4, C14H16O2, C14H20O2	
Candida versatilis CGMCC 3790	Enzyme	AFB1	adsorption+enzymatiqual action	C14H10O4,C14H12O3,	**Li *et al.*(2018)**
	ND*			C13H12O2,C11H10O4.	
Phanerochaetesor-didaYK-624	Manganese ProteaseMnP	AFB1	oxidation+ hydrolyse	AFB1-8,9-dihydrodiol	**Wang *et al.*(2011)**
Rhodos poridium Paludigenum	Enzyme ND*	PAT	ND	Desoxypatulini cacid	**Zhu *et al.*(2015)**
Bacillus pumilus ES-21	Esterase	ZEN	cleavage Lactone ring Fellowed by carboxilation, the process follows First order kinetics with t½ of 6.52h	1-(3.5-dihydroxyphenyl)-60-DesHydroxyl-10-undecen-100-Enzymaticone	**Wang *et al.*(2017)**
Eggerthella sp	Enzyme ND*	DON,HT-2,T-2triol T-2tetraol	De-epoxidation	De-epoxy- DON, de-epoxy T-2triol, de-epoxy HT-2, de-epoxy T-2 tetraol for the04 parents in different ratios	**Gao *et al.*(2018)**
S. cerevisiae	Endo and Exo enzymes Synthtized by The Yeast during The fermentation	PAT	the mecanisme enzymatique and production of relevant PAT metabolizing enzyme synthetized By yeast .cells is not induced by PAT preincubation	Ascladiol	**Li *et al.*(2018)**
Sporobolomyces sp. IAM 1348	ND*	PAT	the mechanism was induced by prtreatment with PAT	DPA and(Z)-ascladiol	**Ianiri *et al.*(2017)**
Pediococcus parvulus UTAD	peptidase	OTA	hydrolysis of the OTA amide groupe	Otα	**Abrunhosa *et al.*(2014).**
Rhizopus and *Aspergillus* species zearalenol-sulfate		ZEN	glycosylation sulfate-conjugation	ZEN-14-sulfate, ZEN-O-14, ZEN- O-16-glucoside, α-zearalenol, α-	**Koch *et al.*(2014).**
Phaffiarhodozyma	Metalloproteas e	OTA	ND	Otα	**Peteri *et al.*(2007)**
Gut Microflora of Pigs	ND	DON	D-epoxydation	De-epoxy-DON	**Kollarczik *et al.* (1994)**
Gut Microflora of Pigs	ND	ZEN	Hydrolyse	α-zearalenol	**Kollarczik *et al.*(1994).**
Bacillus subtilis UTB1	Gene BacC	AFB1	reduction in the double bond Hydrolysis of Ester	AFD1	**Afsharmanesh *et al.*(2018).**

			bond Des carboxylation		
Pseudomonas putida	ND	AFB1	opning of the lactone ring	AFD1,AFD2,AFD3	**Samuel *et al* .(2014)**
Pichiacaribbica	Intracellular enzyme	PAT	Unidentified	ascladiol and unknown compound	**Zhang *et al*.(2018)**

***ND : not determined**

III.3.3.2. Bacteria

Several bacterial species are capable of binding or transforming mycotoxins into less harmful compounds **(Ben Taheur *et al*., 2019).** For instance, Flavobacterium aurantiacum B-184 has been reported to remove AFs from solutions, whereas Enterococcus faecium sequesters AFB1 through interactions with cell wall peptide glycans and polysaccharides (Nesic et al., 2021). Similarly, aerobic oxidation of DON by Devosia spp. converts the toxin into less toxic C3-carbon fragments (Peng et al., 2018).Lactic acid bacteria (LAB) such as *Lactobacillus casei*, *L. reuteri*, *L. amylovorus*, and *L. rhamnosus* can bind up to 60% of AFB_1 in vitro. Moreover, fermentation of whole-grain sorghum by *L. fermentum* resulted in a 98% reduction of FB1 and 84% of T-2 toxin **(Majumdar *et al*., 2021).**

A wide range of bacteria have been reported to degrade mycotoxins, including lactic acid bacteria **(Sadiq *et al*., 2019)** and various other species **(Akbar *et al*., 2022).** For example, *Tetragenococcushalophilus* **(Li *et al*., 2018),** *Rhodococcuserythropolis*, and *Mycobacterium fluoranthenivorans* **(Teniola *et al*., 2005)** have shown effectiveness in degrading AFB_1 . Likewise, *Pediococcusparvulus* **(Abrunhosa *et al*., 2014)** and *Lactobacillus acidophilus* **(Fuchs *et al*., 2015; Wochner *et al*., 2019)** are effective against OTA, AFB1, and AFM1, while *Bifidobacterium animalis* **(Tan *et al*., 2015; Marina *et al*., 2019)** shows promise for PAT control. Additionally, *Pseudomonas otitidis* and *Bacillus velezensis* strain ANSB01E are capable of detoxifying ZEN **(Tan *et al*., 2019; Guo *et al*., 2019).**

The degradation process depends on various factors, including incubation time, medium composition, microbial species, cell concentration, and pH. For instance, thermophilic compost microbiota derived from agricultural waste were able to degrade AFB_1 within five days, achieving more than 95% degradation in PCS medium at 55 °C **(Wang *et al*., 2017).** *Rhodococcuspyridinivorans* K408 detoxified AFB_1 in bioethanol medium within 12 days **(Prettl *et al*., 2017).** On the other hand, *Lacticaseibacillusrhamnosus* strains LGG and LC705 removed AFB_1 very rapidly **(El-Nezami *et al*., 1998).**

The medium also influences detoxification efficiency. For example, *Bacillus subtilis* UTBSP1 showed higher AFB1 detoxification in pistachio nuts compared to culture medium **(Farzaneh *et al*., 2012)**. *Pseudomonas fluorescens* strain 3JW1 degraded AFB_1 by 97.8% in potato dextrose broth and by 99.4% in shelled peanut medium **(Yang *et al*., 2018).**

Numerous bacterial species are capable of degrading multiple mycotoxins simultaneously. *Rhodococcus pyridinivorans* strains K408 and AK37 degraded AFB_1 , T-2 toxin, and ZEN concurrently **(Cserháti *et al.*, 2013).** A microbial consortium, TADC7, also showed similar multipotent degradation activity **(Wang *et al.*, 2018).** Some LAB strains have demonstrated the ability to degrade multiple mycotoxins **(Juodeikiene *et al.*, 2018; Bartkiene *et al.*, 2018).** Notably, *P. fluorescens* 3JW1 not only degraded AFB_1 but also inhibited its production by *A. flavus*, reducing AFB_1 levels by 97.8%, 99.4%, and 55.8% in culture medium, shelled peanut medium, and peanut kernels, respectively **(Yang *et al.*, 2017).**

pH also plays a crucial role in mycotoxin biodegradation. For example, *Alcaligenes faecalis* strain ANSA176 detoxified OTA to OTα within 12 hours at 37 °C, with optimal pH ranging from 6.0 to 9.0. The bacterial strains tested failed to grow at pH values between 2.5 and 5.0 **(Zheng *et al.*, 2022).**

In conclusion, microbial biodegradation of mycotoxins represents a promising strategy, yet it is strongly dependent on several critical parameters. Rigorous studies are necessary to determine optimal conditions for each biocontrol strain. Table 10 provides an overview of bacterial detoxification capabilities across various mycotoxins and culture media and summarizes the degradation of AFB1 by bacterial strains, highlighting both the detoxification efficiencies and the conditions used.

Table 10. detoxification mycotoxins by bacteria

Bacteria	toxins	Median culture	Mains effects	references
Enterococcus faecium M74	PAT	Medium culture Enriched with patulin solution	patulin removalof 15.8 to 41.6 for M74 strain andEF031 strain 19.5 to 45.3for EF031strain	**Tobcu *et al*.(2010)**
Bacillus pumilus ES-21	ZEA	Medium culture with ZEN standard	the degradation rate was more than 95.7%	**Wang *et a*l.(2017)**
Bacillus Amyloliquefaciens ZDS-1	ZEA	(1)Medium culture with ZEN standard (2)contaminated Wheat simple	ZEN degradation with a concentration ranging from 1mg/L to 100mg/L for specific optimal Conditions which are Temperature 30°C,PH from6.0 to 7.0 and a microorganism Concentration of 5.1×10*8 CFU/ml	**Xu *et a*l.(2016)**
Rhodococcu pyridinivorans strains (K408 and AK37)	AFB1, T2 toxin, ZEA	Medium culture with mycotoxin standard	degradation of 3 mycotoxins and increase in the ZONdegradation capacityfrom60% to 95% in the multi- mycotoxin degradation system	**Cserhát *et al*.(2013)**
Microbial consortium TADC7	AFB1	Medium culture	degradation of AFB1by 98.9%	**Wang *et al*.(2018)**
	ZEN	With mycotoxinsand ZEN by 88.5% after 168h Standard solution		
Pseudomonas otitidis TH-N1	ZEA	Medium culture with a ZEN stabdard 2.mM	degradation of ZEN under optimal condition :37°C,pH4 to pH5 and bacterial concentration of 10*9CFU/ml	**Tan *et al*.(2015)**
Bacterial consortium PGC-3	DON,NIV	Medium culture with mycotoxin standard solution.	biotransformation of DON into de-depoxy-DON and NIV with Optimal condition of pH5-10 And temperature of20-37° In aerobic conditions	**He *et al*.(2016)**
Lactic acid bacteria	DON, T-2, HT-2, ZEN	Malting wheat	reduction of the amount of DON and ZEN respectively23%,34%,58% and 73% in Malting wheat simple	**Juodeikiene *et al*.(2018)**
Lactic acid bacteria	FB1, ZEN	Maize meal	reduction in ZEN of68.3% and FB1 of 75% after 4 incubation days	**Mokoena *et al*.(2005)**
Limosilactobacillus reuteri (previously *Lactobacillus reuteri*°	ZEN	Nutrient broth and maize kernel	hydrolysis of 5.0mg/L ZEN for8 h in nutrient broth and hydrolysis Of 2.5mg/kg ZEN for 4h in ZEN Contaminated maize kernels.	**Liu *et al*.(2019)**

Bacillus velezensis StrainANSB01E	ZEN	liquid medium and moldy corn	ZEN degradation of 95% in liquid medium and of 25%in Moldy corn after 48h	**Guo *et al*.(2019)**

III.3.3. 3. Yeasts

The probiotic yeast *Saccharomyces cerevisiae* has demonstrated the ability to degrade DON and reduce DON-induced lactate dehydrogenase (LDH) release in cells **(Jakopovic *et al*.,2018).** Additionally, its cell wall components are capable of adsorbing AFB1 and OTA in poultry feed.

Other yeast species, such as *Kluyveromycesmarxianus*, *Candida utilis*, and *Yarrowialipolytica*, also exhibit strong mycotoxin-binding or -reducing activities against AFB_1 , OTA, and zearalenone (ZEA). *Rhodotorulamucilaginosa* JM19, for example, can degrade patulin (PAT) into dexipitulic acid. Under optimal conditions (35 °C, 1×10^8 cells/L, 21 h), this strain achieves up to 90% PAT reduction **(Li *et al*., 2019).**

Yeasts employ various mechanisms to detoxify mycotoxins, including biodegradation, bioadsorption, and inhibition of mycotoxin biosynthesis **(Papp *et al*., 2011)**. Biodegradation may occur either through enzymatic activity (from isolated enzymes or whole cells) or via direct interaction with the yeast. For instance, Cao *et al*. **(2011)** demonstrated the degradation of AFB1 by an oxidase enzyme isolated from *Armillari ellatabescens*. The degradation was confirmed using HPTLC, and the mechanism was suggested to involve cleavage of the bisfuran ring of the AFs molecule.

Meyerozyma guilliermondii has shown promising activity in controlling patulin contamination in pears. Its detoxification efficiency increases with higher yeast cell concentrations and is effective at both 20 °C and 4 °C, in pear wounds as well as whole fruits **(Yang *et al*., 2022).**

In addition to biodegradation, yeasts can remove mycotoxins via bioadsorption. Certain *S. cerevisiae* strains can eliminate OTA by adsorption, which can be enhanced (from 45% up to 90%) through thermal treatment of the yeast cells and acidification of the medium **(Bejaoui *et al*., 2004).** Similarly, the addition of sugar at 30 °C has been reported to improve OTA reduction by *S. cerevisiae* in semi-synthetic media **(Petruzzi *et al*., 2017).**

The binding capacity of *S. cerevisiae* residues from brewing processes against AFB_1 , ZEA, OTA, and DON was evaluated by Campagnollo *et al*. **(2015)**. Results showed particularly high ZEA binding activity (75.1% at pH 3.0 and 77.5% at pH 6.5). Volatile compounds produced by non-fermenting yeasts have also demonstrated significant binding activities, with the highest efficiencies recorded for OTA (92%), AFB_2 (66%), AFG_2 (59%), and AFB_1 (31%) **(Liang *et al*., 2020).**

However, yeast-based mycotoxin detoxification can sometimes be reversible. For example, *S. cerevisiae* CECT 1891 and *Lactobacillus acidophilus* 24 were able to remove FB1 from liquid media in a rapid but reversible manner **(Pizzolitto *et al.*, 2012)**. The complexity of yeast–mycotoxin interactions highlights the importance of cell wall structural integrity, morphology, and chemical composition in the adsorption process. Future strategies could involve combinations of different microorganisms to provide synergistic benefits.

Yeasts can also inhibit mycotoxin biosynthesis. **Ponsone *et al.* (2011)** studied the biocontrol potential of several yeast strains isolated from Argentine vineyards against ochratoxigenic*Aspergillus* section *Nigri*. Their findings revealed significant reductions in *A.s carbonarius* and *A. niger* growth and OTA accumulation, achieving at least a 50% decrease under various water activity (a_w) and temperature conditions. Similar results were observed by **Fiori *et al.* (2014)**, who used non-fermenting and low-fermenting yeasts to reduce OTA levels in grape juice. However, it should be noted that some yeast strains may only inhibit fungal growth without affecting mycotoxin production.

Table 11. Detoxification of major mycotoxins by yeast strains. Emphasis is placed on culture media and environmental conditions influencing detoxification efficacy.

Yeast	Toxin	medium culture	main effects	references
S. (BEA) Cerevisiae	Beauvericin	(1) standard of BEA (2) corn flour	in total 89.1to99.3%degradation rate in the standard solution against 73.5 to91%in the corn flour	**Meca *et al*.(2013)**
Rhodosporidium Paludigenum	PAT	patulin standard	removal of total amount of patulin after 2 days at 28°C	**Zhu *et al*. (2015)**
Armillariella tabescens	AFB1	AFB1 standard a mixture ofring steamed	cleavage of bis-furan	**Cao *et al*.(2011)**
C. versatilis CGMCC 3790	AFB1	soybean anddegradation dependant baked Wheat flouron initial AFB1		**Li *et al*.(2018)**
Rhizopus stolonife	OTA	wheat contaminated By OTA	degradation of 96.5% of OTA	**Varga *et al*.(2005)**
C. intermedia Lachancea Thermotolerans candida friedrichii Candida tropicalis	OTA	Grape juice	reduction of OTA by *candida intermedia lachancea thermotolerans candida friedchilli* of 73%75%and 70%respectively	**Fiori *et al*.(2014)**
Torulasporadelbriickii, Zygosaccharomyces rouxii, and *Saccharomyces* strains	ZEN	Growth media	biodegradation of ZEN into α-zearalenol and β-zearalenol	**Bdswald *et al*.(1995)**
S.Cerevisiae W13	OTA	Semi-synthetic medium	removal of an amount of OTA from 6to 57.21% with the highest level obtained at 30°C with 250g/L of sugar	**Petruzzi *et al* .(2014)**

III.4. Enzymatic Detoxification

Enzymatic detoxification of mycotoxins combines the advantages of both chemical and biological processes. It offers high efficiency and specificity under mild conditions without posing toxicity risks to organisms. Enzymes act as catalysts in non-stoichiometric ratios, enabling the degradation of mycotoxins **(Lyagin *et al*., 2019)**. Certain *Aspergillus* species are known to produce enzymes capable of detoxifying FB1, including those produced by *Fusarium* spp. **(Burgess *et al*., 2016).**

The activity of enzymes such as β-1,3-glucanase and chitinase against pathogenic fungi varies depending on the specific characteristics of the microorganism **(Lyagin *et al*., 2019).** For instance, Cence *et al*. **(2019)** demonstrated that β-glucanase (50%) and chitinase (50% and 40%) significantly inhibited the growth of Penicillium s*implicissimum*, Aspergillus *niger* complex, *Penicillium nalgiovense*, and *A. flavus* on salami surfaces, suggesting their potential as safe biocontrol agents for fungal spoilage in the fermented meat industry.

In addition, microbial enzymes such as manganese peroxidase, oxidases, catalase, and laccase have been investigated for their potential to detoxify AFB1 **(Sarrocco *et al*., 2019).** Despite their promising toxicological profiles and substrate specificity, the use of enzymes for mycotoxin detoxification remains underexplored. To date, no enzymatic detoxification product has been officially approved in the European Union for the removal of mycotoxins from food products **(Shanakhat *et al*., 2018). Figure19** represent biodegradation enzymatic .

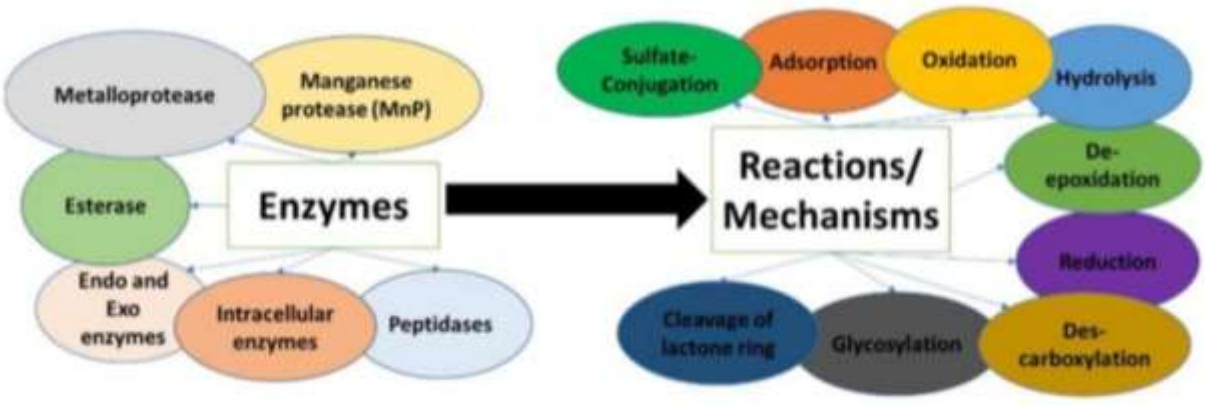

Figure 19 : Mycotoxin biodegradation : enzymes and reactions/mechanisms

(Ndiaye *et al*.,2022).

Microbial degradation of mycotoxins primarily involves a variety of enzymes, including proteases, esterases, and intracellular enzymes, among others. The degradation process may consist of one or several types of biochemical reactions. The main mechanisms described to date include oxidation, hydrolysis, cleavage of the lactone ring, decarboxylation, de-epoxidation, glycosylation, and sulfate conjugation.

These enzymatic transformations contribute significantly to the detoxification of various mycotoxins by altering their chemical structure and reducing their toxicity. Figure 2 provides a general overview of the enzymes implicated in mycotoxin degradation by microorganisms, along with the types of reactions involved.

Furthermore, one notable detoxification mechanism includes the suppression of the non-ribosomal peptide synthetase gene (*otanpsPN*) involved in the OTA biosynthetic pathway. This downregulation was observed by Peromingo *et al*. **(2018)**, suggesting a potential regulatory target for OTA mitigation.

III.5. Novel Detoxification Strategies

Mycotoxins, toxic secondary metabolites produced by fungi, pose serious threats to human and animal health. Traditional detoxification approaches including physical sorting, thermal processing, and chemical treatments often suffer from limited efficiency, specificity, or safety. Consequently, innovative strategies have been developed with a focus on selectivity, environmental sustainability, and food safety.

III.5.1. Nanoparticles

Recent studies have highlighted the potential of nanoparticles as promising adsorbents or degradative agents for mycotoxin removal. Magnetic carbon nanocomposites have been successfully applied for the detoxification of AFB1, while chitosan-coated Fe^2O^2 nanoparticles have demonstrated effectiveness against PAT. Silver nanoparticles have also been shown to degrade *Fusarium* species and their associated mycotoxins **(Luo *et al*., 2018; Tarazon *et al*., 2019).**

An emerging photocatalytic nanoparticle, UCNP@TiO_2 (upconversion nanoparticle–titanium dioxide composite), has been synthesized and evaluated for the degradation of DON. This system reduced DON concentrations in cereal products to below the regulatory limit (1 ppm) after 90 minutes of illumination, with complete degradation achieved after 120 minutes. Importantly, the breakdown products were reported to be only slightly toxic or even non-toxic, positioning UCNP@TiO^2 as an

efficient and environmentally benign detoxification method **(Zhou *et al*., 2020).**González-Jartín *et al*. **(2019)** further demonstrated the elimination of up to 87% of various mycotoxins using nanocomposites comprising activated carbon, bentonite, and aluminum oxide.

III.5.2.Essential Oils (NEOs)

Essential oils (NEOs) and their bioactive constituents have been widely studied for their antifungal and antimycotoxigenic properties (**Sanzani *et al*., 2016;Chaudhari *et al*., 2019).** These natural products can inhibit fungal growth and reduce mycotoxin biosynthesis, making them attractive alternatives to synthetic fungicides due to their safety and environmental compatibility.

Studies have shown that clove oil and its principal compound, eugenol, as well as turmeric essential oil, can inhibit the growth of *Aspergillus* species and suppress AFB1 production. Application of whole clove to culture media and rice grains significantly reduced growth and toxin production of *A. flavus* and *P. citrinum* **(Aiko *et al*., 2015;Umesh *et al*., 2017).**

Sánchez-Montero *et al*. **(2019)** reported that Spanish smoked paprika (Pimentón de la Vera) at concentrations of 2–3% added to meat products such as fillets and sausages suppressed the growth of *A. parasiticus* and *P. nordicum*, and the production of AFB1, AFG1, and OTA. Similarly, capsaicin was found to reduce OTA production in grapes by *Aspergillus* section *Nigri* strains (by 28.9–78.1%) and by 61.5% in *A. carbonarius* **(Kollia *et al*., 2019).**

NEOs are known to interfere with fungal cell structure and function by disrupting membrane integrity, modulating gene expression, and inhibiting enzymes involved in carbohydrate metabolism and mycotoxin synthesis **(Tian *et al*., 2011; Cai *et al*., 2022).** For instance, *Origanum majorana* essential oil exhibited significant antifungal activity in vitro by inhibiting *A. flavus* growth and aflatoxin production **(Chaudhari *et al*., 2020)**. Additionally, garlic, rosemary, sage, and mint essential oils have been shown to inhibit OTA synthesis, while turmeric oil strongly reduced aflatoxin contamination in maize. According to Kedia *et al*. **(2016),** *Mentha spicata* essential oil inhibited mycotoxin production in *A. flavus*-infected chickpeas by targeting the fungal plasma membrane. Essential oils from lemon, grapefruit, and eucalyptus were also effective against ZEN production. Recent studies have further confirmed that *Curcuma longa* essential oil inhibited *Fusarium graminearum* growth and ZEN production **(Kumar *et al*., 2016).**While NEOs offer promising natural solutions for mycotoxin control, their practical application faces several challenges. These include variable efficacy depending on the mycotoxin type and environmental conditions, potential sensory impacts on food products due to strong aromas and flavors, and a lack of regulatory standards.

Moreover, concerns persist regarding their cost, potential residues, environmental impact during production, instability, and allergenicity, which may limit their widespread adoption.

Although numerous studies have demonstrated the inhibitory effects of EOs on fungal growth and OTA production, most investigations have focused on *A. ochraceus*, while their activity against *A. carbonarius* remains poorly understood **Table 12.**

Table 12. Effect of essential oils on the growth of ochratoxigenic fungi. MFC: minimum fungicidal concentration.

Essential oils	Fungal	Concentration and effect on fungal biomass	References
Thyme	*A.Ochraceus*	0.5µL/mL(CMF)	**Soliman & Badeaa.(2002)**
Basil	*A.Ochraceus*	3 µL/mL(CMF)	**Soliman & Badeaa.(2002)**
Cinnamon	*A.Ochraceus*	500µL/mL(CMF)	**Hua *et al*.(2014)**
Green Mint	*A.Ochraceus*	2µL/mL(CMF)	**Soliman&Badeaa.(2002)**
Fennel	*A.Ochraceus*	2 µL/mL(CMF)	**Soliman&Badeaa.(2002)**
Anise	*A.Ochraceus*	>40 µL/mL(CMF)	**Hua *et al*.(2014)**
Cumin	*A.Ochraceus*	3 µL/mL(CMF)	**Soliman&Badeaa.(2002)**
Chamomile	*A.Ochraceus*	3 µL/mL,71% Inhibition	**Soliman&Badeaa.(2002)**
Origano	*A.Ochraceus*	0.75 µL/mL(CMF)	**Basilico &Basilico.(1999)**
	A.carbonarius	0.25m/L ,95.6%inhibition	**Kocic-Tanackov *et al*.(2012)**
	A.niger	0.25 µL/mL,45.6% Inhibition	
Mint	*A.Ochraceus*	1 µL/mL(CMF)	**Basilico &Basilico (1999)**
Sage	*A.Ochraceus*	1 µL/mL,30% Inhibition	**Basilico&Basilico (1999)**
Lemon-scented lits (litsea citrate)	*A.Ochraceus*	500µL/Ml (CMF)	**Hua *et al*.(2014)**
Clove	*A.Ochraceus*	>3000 µL/mL(CMF)	**Passone*et al*.(2012)**
	A.niger	3000 µL/mL(CMF)	

III.5.3 Polyphenolic Compounds

Polyphenols have garnered considerable attention due to their broad spectrum of biological activities, including antimicrobial, antiviral, and anti-inflammatory properties **(Mehany *et al*., 2021).** They exert multiple mechanisms of action against mycotoxins, such as antioxidant activity, lipophilicity, down regulation of genes involved in mycotoxin biosynthesis, and inhibition of key enzymatic pathways **(Hamad *et al*., 2021).** Plant extracts rich in polyphenols have demonstrated the ability to suppress fungal growth and significantly reduce mycotoxin levels. For instance, Sanzani *et al.* **(2009)** reported that compounds like umbelliferone and quercetin can downregulate genes associated with PAT biosynthesis, thereby decreasing its accumulation. Similarly, chlorogenic and gallic acids have been shown to inhibit AFB1 production in legumes **(Telles *et al*., 2017).** Moreover, Salas et al. **(2012)** found that citrus flavanones, including hesperidin and naring²in, reduced PAT synthesis by up to 95%. A nanosponge system based on β-cyclodextrin combined with bioactive phenolic compounds has also proven effective in preventing fungal infections and detoxifying mycotoxins **(Makhuvele *et al*., 2020)**. In addition to their antifungal and antitoxin activities, these natural substances possess antioxidant and therapeutic potential, which may mitigate the adverse effects of mycotoxin exposure **(Sharma *et al*., 2021).** Recent findings continue to underscore the promising role of polyphenols in reducing the toxicological impact of fungi and their metabolites, highlighting their potential for future applications in food safety and preservation

Conclusion

Mycotoxins continue to pose a significant global challenge due to their wide spread occurrence, high toxicity, and persistence in diverse food matrices. Their impact on public health, food security, and economic stability is substantial, especially in regions with limited monitoring infrastructure. Conventional detection techniques such as GC, HPLC, and LC-MS, while accurate, remain costly and technically demanding, restricting their applicability for large-scale routine screening.

Recent advances in rapid and cost-effective detection methods—including ELISA, biosensors, and lateral flow assays—have improved accessibility, yet limitations remain in terms of sensitivity, specificity, and the ability to detect multiple toxins simultaneously. In this context, the integration of artificial intelligence offers a transformative approach. AI-driven models, particularly those based on machine learning and deep learning, have shown great potential in enhancing the detection, classification, and prediction of mycotoxin contamination with high precision. These technologies enable real-time analysis and support decision-making processes for timely intervention.

Simultaneously, growing interest in non-thermal, environmentally friendly decontamination strategies such as cold atmospheric plasma, polyphenols and flavonoids, natural essential oils, and nanotechnology reflects the urgent need to mitigate mycotoxins risks without compromising food quality.

Future perspectives should prioritize the development of robust, multiplex, and field-deployable detection platforms that combine biosensor technologies with AI algorithms. Moreover, efforts should focus on standardizing AI-based systems to ensure reproducibility and regulatory acceptance. Interdisciplinary collaboration among food scientists, microbiologists, data scientists, and policy makers will be crucial to translate these technological innovations into scalable solutions. Ultimately, the convergence of smart detection systems and sustainable mitigation approaches promises a safer and more resilient global food supply chain.

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