

Mycotoxins Unveiled: Analytical Detection, Toxicology and Detoxification

Bhanu Sree Chintaparthi¹, K. Sathiya Bama¹, S. Suganya¹, T. Kalaiselvi²,
S.P. Sangeetha³

¹Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India, ²Department of Microbiology, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India, ³Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India

Abstract

Soil is a major reservoir through which fungal mycotoxins enter the food chain; however, their behavior once they leave the plant and enter the soil remains poorly characterized. This review synthesizes the pharmaceutical, analytical, and agronomic literature on soil-borne mycotoxins to clarify their sources, environmental fate, detection, and mitigation. *Aspergillus*, *Fusarium* and *Penicillium* persist between cropping seasons as sclerotia and crop debris and, under favorable temperature and moisture, synthesize aflatoxins, fumonisins, deoxynivalenol, ochratoxin A and zearalenone. These toxins bind to clay minerals and humic substances, governing their soil persistence and eventual transfer to crops, where they cause hepatocarcinogenicity, nephrotoxicity, immunosuppression, and endocrine disruption. Liquid chromatography–mass spectrometry (LC-MS)/MS and ultra-high-performance LC coupled with high-resolution MS remain the analytical gold standard, although humic-acid interference and inconsistent soil-extraction protocols limit reliable quantification; nanotechnology-based biosensors and precision-agriculture tools are emerging as faster alternatives. Atoxigenic *Aspergillus flavus* biocontrol, biochar amendment and climate-resilient cultivars each show encouraging field-scale efficacy as mitigation strategies; however, none has been validated within a fully integrated soil-management program. We conclude that standardizing soil-extraction protocols and integrating biological, agronomic, and precision-agriculture strategies are the priority steps for managing soil-mycotoxin risk to agricultural, food-safety, and pharmaceutical stakeholders.

Key words: Aflatoxin, biochar, biological control, climate change, food safety, liquid chromatography–mass spectrometry/mass spectrometry, soil mycotoxins

INTRODUCTION

Soil is a highly dynamic and biologically active ecosystem harboring extraordinary microbial diversity. A single gram of fertile soil may contain billions of microbial cells representing thousands of species, driving essential ecological processes, including organic matter decomposition, nutrient mineralization, nitrogen fixation, and biological disease suppression.^[1,2] Among these microorganisms, filamentous fungi play dual ecological roles: While many contribute to soil fertility and plant health, others produce biologically active secondary metabolites with profound toxicological significance.^[3,4]

Mycotoxins, toxic secondary metabolites produced by fungi, represent a major class of soil-borne contaminants with far-reaching implications for agricultural productivity, food safety, and public health.^[4-6] Unlike synthetic chemical pollutants, mycotoxins are

natural products synthesized through complex biosynthetic pathways, typically during the stationary phase of fungal growth under environmental stress.^[3,7] The Food and Agriculture Organization estimates that approximately 25% of global food crops are contaminated with mycotoxins annually, although recent multi-mycotoxin surveillance studies suggest the actual prevalence is considerably higher due to widespread co-contamination.^[8,9]

Soil acts as a critical reservoir for mycotoxin-producing fungi, receiving inoculum through infected crop residues,

Address for correspondence:

K. Sathiya Bama, Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India.
E-mail: sathiyabama.k@tnau.ac.in

Received: 08-08-2026

Revised: 05-09-2026

Accepted: 16-09-2026

rhizosphere colonization, and microbial decomposition.^[10] The synthesis, persistence, and bioavailability of these toxins in soil are strongly regulated by environmental factors, including temperature, moisture, nutrient availability, and agricultural practices.^[11] Once established, soil-borne mycotoxins can enter plants through root absorption or contaminate crops during growth and storage, ultimately entering the food chain and posing serious pharmacological risks to humans and animals.^[12,13]

This review distinguishes three related but distinct phenomena that are often conflated in the literature. First, *Toxigenic fungi in soil* refer to the presence and survival of mycotoxin-producing species (e.g., *Aspergillus* and *Fusarium* spp.) as spores, mycelium, or sclerotia in the soil matrix, which does not by itself imply active toxin synthesis. Second, *soil mycotoxins* refer specifically to free toxin molecules already present in the soil matrix, sorbed to clay and humic colloids, or dissolved in soil pore water, regardless of whether the fungus that produced them remains viable at that location. Third, *crop, food and feed contamination* refers to toxin residues that have already been translocated into or synthesized within harvested plant material and is the endpoint most directly relevant to regulatory maximum levels. Conflating these three categories risks overstating the evidence base: For example, detecting toxigenic *Aspergillus flavus* DNA in soil is not equivalent to confirming free aflatoxin in that soil, and neither is equivalent to demonstrating aflatoxin residues in the crop grown there. Where the underlying literature does not distinguish these levels explicitly, this review notes the ambiguity rather than assuming equivalence.

Recent advances in molecular biology, metagenomics and analytical techniques, particularly Liquid chromatography–mass spectrometry (LC-MS)/MS and Ultra-High-Performance LC coupled with High-Resolution MS (UHPLC-HRMS), have considerably improved the detection and mechanistic understanding of mycotoxins in soil ecosystems.^[14,15] Soil mycotoxins sit at an interesting crossroads of microbial

metabolism and mineral surface chemistry: Their sorption, transformation, and eventual release are governed by the same clay–organic matter interactions that determine the fate of other organic pollutants in soil.^[16] A number of gaps in this picture remain unresolved, particularly around the environmental fate of masked and emerging mycotoxins, the lack of a standardized soil extraction protocol, and the long-term performance of remediation strategies once climatic conditions start to shift. This review brings together current knowledge on soil mycotoxins, concentrating on their biosynthetic regulation, mineral- and organic-matter-mediated persistence, toxicological impact, analytical detection challenges, and the management strategies available, viewed through a combined food-safety and pharmaceutical-sciences lens [Figure 1].

MAJOR SOIL MYCOTOXINS: SOURCES AND PERSISTENCE

Aflatoxins

Aflatoxins, produced primarily by *A. flavus* and *Aspergillus parasiticus*, are among the most potent hepatocarcinogenic natural compounds known.^[17] These polyketide-derived toxins persist in agricultural soils as sclerotia and spores, colonizing crop residues and infecting economically important crops such as maize (*Zea mays*), groundnut (*Arachis hypogaea*), cottonseed (*Gossypium* spp.) and tree nuts.^[18] *A. flavus* survives between cropping seasons in soil and spreads through airborne spores that colonize plant surfaces and developing kernels. Environmental stress, particularly drought and high temperature, weakens plant defense mechanisms, facilitating fungal penetration and aflatoxin biosynthesis.^[19] Once produced, aflatoxins enter soil through the decomposition of infected residues, creating a continuous soil–plant–soil contamination cycle.^[10] Chemically, aflatoxin B1 (AFB1) is the most toxic and carcinogenic congener, forming DNA adducts following metabolic activation and



Figure 1: Soil-borne mycotoxin cycle: Fungal contamination of soil, uptake into crops, transfer to human/animal exposure, and analytical and detoxification interventions that interrupt the pathway

strongly associated with liver cancer, immune suppression, and growth retardation in exposed populations.^[20,21]

The International Agency for Research on Cancer (IARC) has classified AFB1 as a Group 1 carcinogen (carcinogenic to humans) with no known safe threshold of exposure.^[17] Regulatory bodies worldwide have established stringent maximum residue limits; the European Union (EU) permits a maximum of 2.0 µg/kg AFB1 in groundnuts and 4.0 µg/kg for total aflatoxins.^[9,17]

Fusarium toxins

Fusarium species are ubiquitous soil-inhabiting pathogens responsible for producing fumonisins, trichothecenes, and zearalenone (ZEN).^[22,23] *Fusarium verticillioides* commonly infects maize and produces fumonisins that disrupt sphingolipid metabolism and cell membrane formation.^[24] *Fusarium graminearum*, the causal agent of *Fusarium* head blight in cereals, synthesizes trichothecenes, such as deoxynivalenol (DON), which inhibit ribosomal protein synthesis and elicit feed refusal, vomiting, and immune dysfunction in mammals.^[25] These fungi persist in soil, plant debris, and infected seeds, serving as recurrent inoculum sources across cropping seasons. In temperate regions, *Fusarium* mycotoxins are projected to increase in prevalence as climate warming shifts optimal conditions northward.^[26]

Fumonisin B1 (FB1) has been classified by IARC as Group 2B (possibly carcinogenic to humans), with strong epidemiological links to neural tube defects and esophageal cancer.^[24] The EU regulates FB1 and FB2 at 4000 µg/kg in unprocessed maize.^[9] DON, while not classified by IARC for carcinogenicity, is one of the most prevalent food contaminants globally, with an EU regulatory limit of 1000 µg/kg in unprocessed cereals (1500 µg/kg for unprocessed durum wheat and maize).^[25]

Ochratoxin A (OTA) and other mycotoxins

Aspergillus ochraceus and *Penicillium verrucosum* produce OTA, a nephrotoxic and potentially carcinogenic mycotoxin frequently detected in stored cereals, coffee and dried fruits.^[27] OTA exhibits extended persistence in clay-rich soils because of strong adsorption to humic substances, increasing its ecological residence time and bioavailability risk.^[28] IARC has classified OTA as Group 2B, with the EU setting a limit of 5.0 µg/kg in raw cereals.^[27]

In addition, *Alternaria* species produce emerging toxins such as alternariol and tenuazonic acid, which are increasingly recognized in agricultural soils but remain largely unregulated. ZEN, produced primarily by *F. graminearum* and *Fusarium culmorum*, exhibits potent estrogenic activity and has been classified by IARC as Group 3 (not classifiable as to its carcinogenicity to humans).^[29] The EU regulates

ZEN at 100 µg/kg in unprocessed cereals other than maize and at 350 µg/kg in unprocessed maize.^[9]

Soil persistence and bioavailability

The environmental fate of mycotoxins in soil is governed by their lipophilic nature, which promotes strong binding to soil organic matter, clay particles, and humic acids.^[10,28] This adsorption can reduce immediate bioavailability but also prolong persistence, creating long-term ecological reservoirs. Mycotoxins may inhibit soil enzyme activities, suppress sensitive microbial populations, and alter rhizosphere community structure, ultimately affecting nutrient cycling and soil fertility.^[29] Understanding the sorption–desorption dynamics of mycotoxins across diverse soil types remains essential for accurate risk assessment [Table 1].

BIOSYNTHESIS AND ENVIRONMENTAL REGULATION

Mycotoxin biosynthesis is genetically encoded by clustered biosynthetic gene clusters (BGCs) that coordinate the expression of polyketide synthases (PKS), non-ribosomal peptide synthetases and tailoring enzymes.^[31,32] The *aflatoxin* gene cluster spans approximately 75 kb and includes aflR, the pathway-specific transcriptional activator, while the fumonisin cluster in *F. verticillioides* encompasses FUM1 (PKS), FUM8 (aminotransferase), and the regulatory gene FUM21.^[33,34] Advances in comparative genomics have revealed that many fungi harbor “silent” or cryptic BGCs, suggesting a far greater metabolic potential than previously recognized.^[35,36]

The environmental regulation of these pathways is complex. Temperature, water activity, oxidative stress, and nutrient limitation serve as primary triggers for secondary metabolite production.^[3,11] Elevated temperatures (25–35°C) and drought stress activate aflatoxin biosynthesis in *A. flavus*, whereas moderate temperatures and high humidity favor *Fusarium* toxin production.^[11,37] Climate change, characterized by rising mean temperatures, altered precipitation patterns, and increased frequency of extreme weather events, is projected to significantly expand the geographical distribution of toxigenic fungi.^[26,38] In Europe, climate models predict that a +2°C temperature increase will increase aflatoxin contamination in southern maize-growing regions, whereas northern Europe may experience elevated DON levels in wheat.^[26,39,40] These shifts challenge existing regulatory frameworks and necessitate proactive monitoring strategies.

TOXICOLOGICAL IMPACTS

Effects on soil microbiome and plant physiology

Mycotoxins have multifaceted ecological effects. In soil, they alter the microbial community composition by

selectively suppressing beneficial bacteria and fungi while favoring resistant strains.^[29,41] This disruption can reduce soil respiration, impair organic matter decomposition, and compromise plant–microbe symbiosis.^[11] In plants, mycotoxins function as phytotoxins that inhibit seed germination, reduce root elongation, and impair nutrient uptake.^[42] Trichothecenes induce oxidative stress through reactive oxygen species generation, leading to lipid peroxidation, membrane damage, and chlorophyll degradation. Fumonisin disrupt sphingolipid metabolism, thereby altering membrane stability and signaling processes in cereal crops.^[24] These physiological disruptions cumulatively reduce photosynthetic efficiency, biomass accumulation and crop yield.

Recent studies have demonstrated that mycotoxin exposure can trigger complex defense responses in plants, including the activation of salicylic acid, jasmonic acid, and ethylene signaling pathways.^[43] Although these responses may confer partial resistance, chronic toxin exposure often overwhelms plant defense systems, increasing susceptibility to secondary infections.

Human and animal toxicology

The most severe consequences of mycotoxin exposure occur through dietary intake. Aflatoxins are classified as Group 1 carcinogens by the IARC, with chronic exposure strongly linked to hepatocellular carcinoma, particularly in individuals coinfecting with hepatitis B virus.^[20,21] Acute aflatoxicosis can be fatal, as demonstrated by outbreaks in Kenya, with case fatality rates exceeding 30%.^[21] Fumonisin is associated with neural tube defects and esophageal cancer, while OTA causes nephropathy and is suspected to contribute to Balkan endemic nephropathy.^[27,28] Trichothecenes, particularly DON, induce gastrointestinal toxicity, immunosuppression, and anorexia at concentrations commonly found in contaminated cereals.^[25,44] ZEN exhibits potent estrogenic activity and acts

as an endocrine disruptor in humans and livestock.^[30]

The co-occurrence of multiple mycotoxins in food and feed matrices may produce additive or synergistic toxic effects, complicating risk assessment and regulatory limit setting.^[9,45,46] Recent human biomonitoring studies across Europe have documented increasing exposure to DON and other *Fusarium* toxins, particularly among children and adolescents, underscoring the urgent need for enhanced surveillance [Figure 2].^[47]

ANALYTICAL DETECTION IN COMPLEX SOIL MATRICES

Chromatographic methods

Accurate quantification of mycotoxins in soil is analytically challenging because of matrix interference from humic substances, clay minerals, and complex organic residues.^[14] LC-MS/MS has emerged as the gold standard for multi-mycotoxin profiling, enabling simultaneous detection of aflatoxins, fumonisins, trichothecenes, OTA, and ZEN at trace concentrations.^[15,48] UHPLC-HRMS offers superior mass accuracy and resolution, facilitating the identification of unknown or emerging toxins through exact mass determination and fragmentation pattern analysis.^[14]

However, the lack of standardized extraction and cleanup protocols for soil matrices remains a significant bottleneck, leading to variable recovery rates and underreporting of soil contamination levels.^[14] Humic and fulvic acids can bind to mycotoxins or interfere with detection signals, complicating toxin extraction and reducing analytical accuracy.^[14] Recent method validation studies have emphasized the need for matrix-matched calibration and isotopically labeled internal standards to improve quantification reliability in soil samples.^[15]

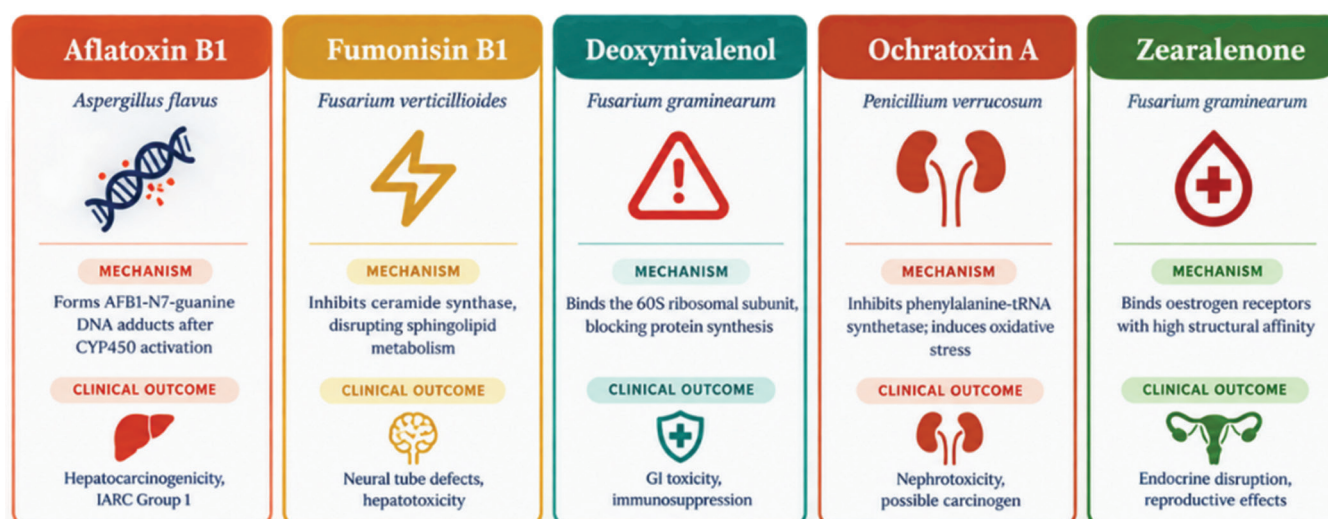


Figure 2: Principal molecular mechanisms and clinical/toxicological outcomes associated with the five major soil-borne mycotoxin classes

Emerging nanotechnology-based biosensors

Nanotechnology has revolutionized mycotoxin detection by developing rapid and portable biosensors. Gold and silver nanoparticles enable colorimetric and surface plasmon resonance detection of AFB1, whereas quantum dots and carbon nanotubes enhance fluorescence and electrochemical sensing performance.^[49,50] Recent advances include paper-based dual-analyte electrochemical nanobiosensors using phosphorene–gold nanocomposites for the simultaneous detection of AFB1 and OTA^[51] and up-conversion nanoparticle-modified aptasensors for highly sensitive immunochromatographic strip assays.^[52]

These technologies hold significant promise for on-site soil monitoring, although their field applicability requires further validation using reference LC-MS/MS methods. The integration of smartphone-based readout systems with aptamer-conjugated magnetic nanoparticles has enabled sensitive AFB1 detection at the picogram level, representing a major advancement in decentralized pharmaceutical analysis.^[49]

REMEDIATION AND MANAGEMENT STRATEGIES

Biological control

Biological control using atoxigenic *A. flavus* strains represents one of the most promising pre-harvest interventions. These endemic, non-toxigenic strains competitively exclude toxigenic genotypes from the rhizosphere and crop niches, reducing aflatoxin contamination by 70–99% in field trials across Africa, Europe and the Americas.^[53–56] Commercial products such as Afla-Guard, AF36 Prevail and AflaSafe have demonstrated sustained efficacy in maize, groundnut and tree nut systems.^[55]

The studies have indicated that selected atoxigenic strains can degrade existing aflatoxin residues through metabolic utilization, offering dual protective mechanisms.^[56] However, the selection of regionally endemic strains is critical to ensure ecological compatibility and minimize the risk of genetic recombination with local toxigenic populations.^[54] This mechanism involves competitive exclusion through the rapid colonization of crop tissues and the production of inhibitory metabolites that suppress the growth of toxigenic fungi.

Soil amendments and biochar

Soil amendments, particularly biochar produced through biomass pyrolysis, exhibit high adsorption capacity for mycotoxins owing to their extensive surface area, microporous structure, and abundant functional groups.^[57,58] Biochar application reduces toxin bioavailability and mobility in soil^[59] while simultaneously improving soil physicochemical

properties, nutrient retention, and beneficial microbial community structure.^[57] The adsorption mechanisms involve hydrophobic partitioning, π – π electron donor–acceptor interactions, hydrogen bonding, and pore-filling effects.^[58]

Research has demonstrated that biochar can significantly reduce the bioavailability of mycotoxins in soil, thereby minimizing their harmful effects on plants and soil organisms.^[59] Nevertheless, the long-term stability of biochar–mycotoxin complexes under field conditions and potential ecological risks require further investigation. Organic amendments, such as compost and well-decomposed manure, can also enhance soil microbial diversity and stimulate the activity of beneficial microorganisms capable of degrading or transforming mycotoxins.^[11]

Integrated soil management and precision agriculture

Comprehensive mycotoxin mitigation demands integration of biological control, agronomic practices, and predictive technologies. Crop rotation with non-host species, proper residue management and cultivation of drought-tolerant, disease-resistant crop varieties reduce fungal inoculum and plant stress.^[60] Precision agriculture tools, including soil sensors, climate monitoring systems, geospatial mapping and machine learning-based predictive models, enable early warning systems for high-risk contamination periods, facilitating targeted interventions such as optimized irrigation schedules and timely harvesting.^[61,62] The integration of these approaches within a One Health framework, linking soil health, crop productivity and food safety, is essential for sustainable mycotoxin management [Table 2].

CLIMATE CHANGE AND EMERGING RISKS

Climate change represents a major driver of future mycotoxin risk. Rising temperatures and altered precipitation patterns are expanding the habitable ranges of thermotolerant *Aspergillus* species into temperate regions previously considered low-risk.^[26,38,63] The European Food Safety Authority anticipates that climate change will increase aflatoxin contamination from low to medium risk across European maize-producing regions.^[39,64] Concurrently, extreme weather events, including droughts followed by heavy rainfall, exacerbate plant stress and create favorable conditions for fungal infection and toxin production.^[38,65,66]

The emergence of masked mycotoxins, metabolites conjugated to polar compounds such as glucose, further complicates risk assessment, as these derivatives often evade routine detection^[67,68] but can be hydrolyzed back to parent toxins during digestion.^[69] Recent surveillance data indicate that multi-mycotoxin co-occurrence is the norm rather than the exception

Table 2: Comparison of major remediation and detoxification strategies for soil-borne mycotoxins

Strategy	Mechanism of action	Reported efficacy	Key limitations
Atoxigenic biocontrol (<i>Aspergillus flavus</i>)	Competitive exclusion of toxigenic strains; degradation of existing aflatoxin residues ^[53,56]	70–99% aflatoxin reduction in field trials across Africa, Europe and the Americas ^[53-56]	Requires regionally endemic strains; risk of genetic recombination with local toxigenic populations ^[54]
Biochar amendment	Adsorption via hydrophobic partitioning, π - π interactions, hydrogen bonding, and pore-filling ^[58]	Reduces toxin bioavailability and mobility ^[59] ; improves soil physicochemical properties ^[57]	Long-term stability of biochar–mycotoxin complexes under field conditions not fully established
Organic amendments (compost, manure)	Enhances soil microbial diversity and toxin-degrading microbial activity ^[11]	Supports beneficial microbiota; indirect contamination reduction	Effect size less quantified than biochar; outcomes vary with soil type
Climate-resilient/resistant crop varieties	Reduced fungal inoculum and plant stress via drought and disease tolerance ^[60]	Lowers pre-harvest infection risk	Variety development is slow; regional adaptation required
Precision agriculture and predictive monitoring	Soil sensors, climate monitoring, geospatial mapping and machine-learning-based early warning ^[61,62]	Enables targeted, timely interventions (irrigation, harvest timing)	Infrastructure- and data-intensive; limited accessibility in low-resource settings

in global food supplies, necessitating revised regulatory frameworks that account for additive and synergistic toxicities.^[45]

KNOWLEDGE GAPS AND FUTURE PERSPECTIVES

Despite the progress summarized above, several gaps still limit how confidently soil mycotoxin risk can be assessed. Standardized analytical protocols for extracting mycotoxins from diverse soil types remain elusive, which makes it difficult to compare results across studies or laboratories.^[14] The environmental fate and toxicological significance of masked and emerging mycotoxins in soil–plant systems are also poorly characterized,^[68] and while biological control and biochar amendment both look promising in laboratory and field trials, long-term efficacy data across varied agroecological zones are still thin on the ground.

Most predictive climate models focus almost exclusively on pre-harvest cereal contamination, leaving post-harvest storage dynamics and multi-toxin interactions comparatively understudied.^[39] Going forward, multi-omics approaches that combine genomics, transcriptomics, metabolomics and metagenomics could help unravel the regulatory networks governing mycotoxin biosynthesis in soil microbiomes,^[31,35] and there is a case for exploring whether synthetic biology and microbiome engineering can be used to design beneficial microbial consortia capable of suppressing toxigenic fungi and degrading persistent toxins directly in the field.

CONCLUSION

Soil-borne mycotoxins cannot be treated as a food-safety issue to be measured only after crops are harvested: Their

persistence, mobility and eventual transfer to crops depend on how aflatoxins, fumonisins, trichothecenes and OTA interact with clay minerals, humic substances and the soil microbial community, sustaining a continuous contamination reservoir with knock-on effects for agricultural productivity and public health. LC-MS/MS and nanotechnology-based biosensors have improved detection considerably, but a standardized protocol for extracting mycotoxins from complex soil matrices is still missing, and this remains the principal analytical limitation identified in this review. On the management side, atoxigenic biocontrol, biochar amendment, climate-resilient cultivars, and precision-agriculture tools each offer partial solutions; none has been validated within an integrated soil-management program, and long-term field data across diverse agroecological zones remain scarce. Future work should prioritize standardized soil-extraction protocols, longer-term field trials of combined mitigation strategies, and multi-omics characterization of soil microbiomes within an interdisciplinary effort spanning soil science, analytical chemistry, toxicology, and pharmaceutical sciences.

REFERENCES

1. Torsvik V, Øvreås L. Microbial diversity and function in soil: From genes to ecosystems. *Curr Opin Microbiol* 2002;5:240-5.
2. Van Der Heijden MG, Bardgett RD, Van Straalen NM. The unseen majority: Soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. *Ecol Lett* 2008;11:296-310.
3. Keller NP. Fungal secondary metabolism: Regulation, function and drug discovery. *Nat Rev Microbiol* 2019;17:167-80.
4. Gemedde HF. Toxicity, mitigation, and chemical analysis

- of aflatoxins and other toxic metabolites produced by *Aspergillus*: A comprehensive review. *Toxins* (Basel) 2025;17:331.
5. Wu F, Groopman JD, Pestka JJ. Public health impacts of foodborne mycotoxins. *Annu Rev Food Sci Technol* 2014;5:351-72.
 6. Gadd GM. Geomycology: Biogeochemical transformations of rocks, minerals, metals and radionuclides by fungi, bioweathering and bioremediation. *Mycol Res* 2007;111:3-49.
 7. Kemboi DC, Antonissen G, Ochieng PE, Croubels S, Okoth S, Kangethe EK, *et al.* A review of the impact of mycotoxins on dairy cattle health: Challenges for food safety and dairy production in Sub-Saharan Africa. *Toxins* (Basel) 2020;12:222.
 8. Rodrigues I, Nachrer K. A three-year survey on the worldwide occurrence of mycotoxins in feedstuffs and feed. *Toxins* (Basel) 2012;4:663-75.
 9. Eskola M, Kos G, Elliott CT, Hajšlová J, Mayar S, Krska R. Worldwide contamination of food-crops with mycotoxins: Validity of the widely cited 'FAO estimate' of 25. *Crit Rev Food Sci Nutr* 2020;60:2773-89.
 10. Juraschek LM, Kappenberg A, Amelung W. Mycotoxins in soil and environment. *Sci Total Environ* 2022;814:152425.
 11. Magan N, Aldred D. Post-harvest control strategies: Minimizing mycotoxins in the food chain. *Int J Food Microbiol* 2007;119:131-9.
 12. Alshannaq A, Yu JH. Occurrence, toxicity, and analysis of major mycotoxins in food. *Int J Environ Res Public Health* 2017;14:632.
 13. Loi M, Logrieco AF, Pusztahelyi T, Leiter É, Hornok L, Pócsi I. Advanced mycotoxin control and decontamination techniques in view of an increased aflatoxin risk in Europe due to climate change. *Front Microbiol* 2022;13:1085891.
 14. Ekwomadu TI, Dada TA, Nleya N, Gopane R, Sulyok M, Mwanza M. Variation of *Fusarium* free, masked, and emerging mycotoxin metabolites in maize from agriculture regions of South Africa. *Toxins* (Basel) 2020;12:149.
 15. Malachová A, Stránská M, Václavíková M, Elliott CT, Black C, Meneely J, *et al.* Advanced LC-MS-based methods to study the co-occurrence and metabolization of multiple mycotoxins in cereals and cereal-based food. *Anal Bioanal Chem* 2018;410:801-25.
 16. Raaijmakers JM, Mazzola M. Diversity and natural functions of antibiotics produced by beneficial and plant pathogenic bacteria. *Annu Rev Phytopathol* 2012;50:403-24.
 17. Liu D, Yu H, Luo S, Liang X, Zhang Y, Li Y, *et al.* Aflatoxin contamination and health risk assessment in maize in Gansu Province in 2023. *Food Addit Contam Part A Chem Anal Control Expo Risk Assess* 2025;42:798-806.
 18. Pickova D, Ostry V, Toman J, Malir F. Aflatoxins: History, significant milestones, recent data on their toxicity and ways to mitigation. *Toxins* (Basel) 2021;13:399.
 19. Weaver MA, Park LC, Brewer MJ, Grodowitz MJ, Abbas HK. Detection, quantification, and characterization of airborne *Aspergillus flavus* within the corn canopy. *Mycotoxin Res* 2025;41:267-76.
 20. Wild CP, Gong YY. Mycotoxins and human disease: A largely ignored global health issue. *Carcinogenesis* 2010;31:71-82.
 21. Williams JH, Phillips TD, Jolly PE, Stiles JK, Jolly CM, Aggarwal D. Human aflatoxicosis in developing countries: A review of toxicology, exposure, potential health consequences, and interventions. *Am J Clin Nutr* 2004;80:1106-22.
 22. Munkvold GP. *Fusarium* species and their associated mycotoxins. In: Moretti A, Susca A, editors. *Mycotoxigenic Fungi: Methods and Protocols*. New York: Springer; 2017. p. 51-106.
 23. Placinta CM, D'Mello JP, Macdonald AM. A review of worldwide contamination of cereal grains and animal feed with *Fusarium mycotoxins*. *Anim Feed Sci Technol* 1999;78:21-37.
 24. Marasas WF. Discovery and occurrence of the fumonisins: A historical perspective. *Environ Health Perspect* 2001;109 Suppl 2:239-43.
 25. Pestka JJ. Deoxynivalenol: Mechanisms of action, human exposure, and toxicological relevance. *Arch Toxicol* 2010;84:663-79.
 26. Perrone G, Ferrara M, Medina A, Pascale M, Magan N. Toxigenic Fungi and mycotoxins in a climate change scenario: Ecology, genomics, distribution, prediction and prevention of the risk. *Microorganisms* 2020;8:1496.
 27. Pfohl-Leszkowicz A, Manderville RA. Ochratoxin A: An overview on toxicity and carcinogenicity in animals and humans. *Mol Nutr Food Res* 2007;51:61-99.
 28. Pfohl-Leszkowicz A, Manderville RA. An update on direct genotoxicity as a molecular mechanism of ochratoxin a carcinogenicity. *Chem Res Toxicol* 2012;25:252-62.
 29. Antonissen G, Martel A, Pasmans F, Ducatelle R, Verbrugghe E, Vandenbroucke V, *et al.* The impact of *Fusarium mycotoxins* on human and animal host susceptibility to infectious diseases. *Toxins* (Basel) 2014;6:430-52.
 30. Kowalska K, Habrowska-Górczyńska DE, Piastowska-Ciesielska AW. Zearalenone as an endocrine disruptor in humans. *Environ Toxicol Pharmacol* 2016;48:141-9.
 31. Ferrara M, Perrone G, Gallo A. Recent advances in biosynthesis and regulatory mechanisms of principal mycotoxins. *Curr Opin Food Sci* 2022;48:100923.
 32. Yu J, Chang PK, Ehrlich KC, Cary JW, Bhatnagar D, Cleveland TE, *et al.* Clustered pathway genes in aflatoxin biosynthesis. *Appl Environ Microbiol* 2004;70:1253-62.
 33. Proctor RH, Brown DW, Plattner RD, Desjardins AE. Co-expression of 15 contiguous genes delineates a fumonisin biosynthetic gene cluster in *Gibberella moniliformis*. *Fungal Genet Biol* 2003;38:237-49.
 34. Brown DW, Yu JH, Kelkar HS, Fernandes M, Nesbitt TC,

- Keller NP, *et al.* Twenty-five coregulated transcripts define a sterigmatocystin gene cluster in *Aspergillus nidulans*. *Proc Natl Acad Sci U S A* 1996;93:1418-22.
35. Rokas A, Wisecaver JH, Lind AL. The birth, evolution and death of metabolic gene clusters in fungi. *Nat Rev Microbiol* 2018;16:731-44.
 36. Cary JW, Gilbert MK, Lebar MD, Majumdar R, Calvo AM. *Aspergillus flavus* secondary metabolites: More than just aflatoxins. *Food Saf (Tokyo)* 2018;6:7-32.
 37. Medina A, Akbar A, Baazeem A, Rodriguez A, Magan N. Climate change, food security and mycotoxins: Do we know enough? *Fungal Biol Rev* 2017;31:143-54.
 38. Kos J, Anić M, Radić B, Zadravec M, Janić Hajnal E, Pleadin J. Climate change-a global threat resulting in increasing mycotoxin occurrence. *Foods* 2023;12:2704.
 39. EFSA Panel on Contaminants in the Food Chain (CONTAM), Schrenk D, Bignami M, Bodin L, Chipman JK, Del Mazo J, *et al.* Risk assessment of aflatoxins in food. *EFSA J* 2020;18:e06040.
 40. Van Der Fels-Klerx HJ, Liu C, Battilani P. Modelling climate change impacts on mycotoxin contamination. *World Mycotoxin J* 2016;9:717-26.
 41. Berendsen RL, Pieterse CM, Bakker PA. The rhizosphere microbiome and plant health. *Trends Plant Sci* 2012;17:478-86.
 42. Audenaert K, Vanheule A, Höfte M, Haesaert G. Deoxynivalenol: A major player in the multifaceted response of *Fusarium* to its environment. *Toxins (Basel)* 2013;6:1-19.
 43. Demain AL, Fang A. The natural functions of secondary metabolites. *Adv Biochem Eng Biotechnol* 2000;69:1-39.
 44. Marin S, Ramos AJ, Cano-Sancho G, Sanchis V. Mycotoxins: Occurrence, toxicology, and exposure assessment. *Food Chem Toxicol* 2013;60:218-37.
 45. Gruber-Dorninger C, Jenkins T, Schatzmayr G. Global mycotoxin occurrence in feed: A ten-year survey. *Toxins (Basel)* 2019;11:375.
 46. Skrzydlewski P, Twarużek M, Grajewski J. Cytotoxicity of mycotoxins and their combinations on different cell lines: A review. *Toxins (Basel)* 2022;14:244.
 47. Namorado S, Martins C, Ogura J, Assunção R, Vasco E, Appenzeller B, *et al.* Exposure assessment of the European adult population to deoxynivalenol - results from the HBM4EU aligned studies. *Food Res Int* 2024;198:115281.
 48. Zachariasova M, Dzuman Z, Veprikova Z, Hajkova K, Jiru M, Vaclavikova M, *et al.* Occurrence of multiple mycotoxins in European feedingstuffs, assessment of dietary intake by farm animals. *Anim Feed Sci Technol* 2014;193:124-40.
 49. Liu T, Shu J, Xiao J, Zhou J, Chen Z, Yu Q, *et al.* Covalent organic framework @ magnetic carbon nanotube composite rapidly prepared by mechanochemical method for sensitive determination of AFB1 in real sample. *Food Anal Methods* 2026;19:196.
 50. Gao J, He S, Nag A, Wong JW. A review of the use of carbon nanotubes and graphene-based sensors for the detection of aflatoxin M1 compounds in milk. *Sensors (Basel)* 2021;21:3602.
 51. Jiang H, Guo Q, Liu Y, Qin M, Bikila TL, Weng X. A simple paper-based dual-analyte electrochemical nanobiosensor for mycotoxins using phosphorene-gold nanocomposites. *IEEE Sens J* 2022;22:19144-51.
 52. Bahari HR, Mousavi Khaneghah A, Eş I. Upconversion nanoparticles-modified aptasensors for highly sensitive mycotoxin detection for food quality and safety. *Compr Rev Food Sci Food Saf* 2024;23:e13369.
 53. Bandyopadhyay R, Ortega-Beltran A, Akande A, Mutegei C, Atehnkeng J, Kaptoge L, *et al.* Biological control of aflatoxins in Africa: Current status and potential challenges in the face of climate change. *World Mycotoxin J* 2016;9:771-89.
 54. Mauro A, Garcia-Cela E, Pietri A, Cotty PJ, Battilani P. Biological control products for aflatoxin prevention in Italy: Commercial field evaluation of atoxigenic *Aspergillus flavus* active ingredients. *Toxins (Basel)* 2018;10:30.
 55. Muñoz-Zavala C, Molina-Macedo A, Toledo FH, Telles-Mejía E, Cabrera-Soto L, Palacios-Rojas N. Combating aflatoxin contamination by combining biocontrol application and adapted maize germplasm in northeastern and SouthEastern Mexico. *Biol Control* 2025;204:105727.
 56. Ortega-Beltran A, Atehnkeng J, Augusto J, Mahuku G, Bandyopadhyay R. Aflatoxin biocontrol using native atoxigenic *Aspergillus*. *Annu Rev Phytopathol* 2026;64:379-409.
 57. Rizwan M, Murtaza G, Zulfiqar F, Moosa A, Iqbal R, Ahmed Z, *et al.* Sustainable manufacture and application of biochar to improve soil properties and remediate soil contaminated with organic impurities: A systematic review. *Front Environ Sci* 2023;11:1277240.
 58. Beljin J, Đukanović N, Anojić J, Simetić T, Apostolović T, Mutić S, *et al.* Biochar in the remediation of organic pollutants in water: A review of polycyclic aromatic hydrocarbon and pesticide removal. *Nanomaterials (Basel)* 2024;15:26.
 59. Appell M, Wegener EC, Sharma BK, Eller FJ, Evans KO, Compton DL. *In vitro* evaluation of the adsorption efficacy of biochar materials on aflatoxin B(1), ochratoxin A, and zearalenone. *Animals (Basel)* 2023;13:3311.
 60. Shah L, Ali A, Yahya M, Zhu Y, Wang S, Si H, *et al.* Integrated control of *Fusarium* head blight and deoxynivalenol mycotoxin in wheat. *Plant Pathol* 2018;67:532-48.
 61. Kamilaris A, Prenafeta-Boldú FX. Deep learning in agriculture: A survey. *Comput Electron Agric* 2018;147:70-90.
 62. Inglis A, Parnell AC, Subramani N, Doohan FM. Machine learning applied to the detection of mycotoxin in food: A systematic review. *Toxins (Basel)* 2024;16:268.
 63. Casu A, Camardo Leggieri M, Toscano P, Battilani P. Changing climate, shifting mycotoxins: A comprehensive review of climate change impact on

- mycotoxin contamination. *Compr Rev Food Sci Food Saf* 2024;23:e13323.
64. Battilani P, Toscano P, Van Der Fels-Klerx HJ, Moretti A, Camardo Leggieri M, Brera C, *et al.* Aflatoxin B1 contamination in maize in Europe increases due to climate change. *Sci Rep* 2016;6:24328.
65. Moretti A, Pascale M, Logrieco AF. Mycotoxin risks under a climate change scenario in Europe. *Trends Food Sci Technol* 2019;84:38-40.
66. Platzer A, Cherkaoui Y, Novak B, Schatzmayr G. Investigating the correlations between weather factors and mycotoxin contamination in corn: Evidence from long-term data. *Toxins (Basel)* 2025;17:77.
67. Freire L, Sant'Ana AS. Modified mycotoxins: An updated review on their formation, detection, occurrence, and toxic effects. *Food Chem Toxicol* 2018;111:189-205.
68. Berthiller F, Crews C, Dall'Asta C, Saeger SD, Haesaert G, Karlovsky P, *et al.* Masked mycotoxins: A review. *Mol Nutr Food Res* 2013;57:165-86.
69. Daud N, Currie V, Duncan G, Farquharson F, Yoshinari T, Louis P, *et al.* Prevalent human gut bacteria hydrolyse and metabolise important food-derived mycotoxins and masked mycotoxins. *Toxins (Basel)* 2020;12:654.

Source of Support: Nil. **Conflicts of Interest:** None declared.