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FOODBORNE MYCOTOXINS AND THE HUMAN MICROBIOME: A HACCP-BASED RISK ASSESSMENT APPROACH

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INTRODUCTION

Mycotoxins are toxic secondary metabolites produced by fungi such as Aspergillus, Fusarium, and Penicillium. They contaminate staple foods including cereals, nuts, coffee, dried fruits, and spices, and represent one of the most significant chemical hazards in food safety (Khan, 2024). Chronic exposure to mycotoxins has long been associated with hepatotoxicity, nephrotoxicity, immunosuppression, and carcinogenesis (Mafe & Büsselberg, 2026).

Evidence indicates that mycotoxins disrupt microbial diversity, reduce beneficial taxa, and promote dysbiosis. For example, deoxynivalenol (DON) impairs short chain fatty acid production and increases intestinal inflammation (Mafe & Büsselberg, 2026), while aflatoxin B_1 alters microbial composition and epithelial barrier integrity (Khan, 2024).The Hazard Analysis and Critical Control Points (HACCP) framework provides a systematic approach to identifying and controlling hazards at critical points in food production.

Applying HACCP principles to mycotoxin contamination involves monitoring agricultural practices, storage conditions, and processing steps where fungal growth and toxin production are most likely (Khan, 2024).

TYPES OF FOODBORNE MYCOTOXINS

Aflatoxins

Produced mainly by Aspergillus flavus and A. parasiticus, aflatoxins are potent hepatotoxins and carcinogens. Aflatoxin B_1 is the most toxic, linked to liver cancer and immune suppression (Mafe & Büsselberg, 2024).

Ochratoxin A (OTA)

Generated by Aspergillus and Penicillium species, OTA contaminates cereals, coffee, and dried fruits. It is nephrotoxic and immunotoxic, and recent findings suggest

Fumonisins

Produced by Fusarium verticillioides, fumonisins contaminate maize and maize based products. Fumonisin B_1 interferes with sphingolipid metabolism and has been associated with esophageal cancer (Mafe & Büsselberg, 2024).

Deoxynivalenol (DON)

Also known as vomitoxin, DON is produced by Fusarium graminearum and contaminates wheat, barley, and maize. DON induces gastrointestinal distress and immune dysregulation.

Zearalenone (ZEN)

Produced by Fusarium species, ZEN is an estrogenic mycotoxin found in maize and wheat. It disrupts hormonal balance and reproductive health.

MICROBIOME IMPACTS OF FOODBORNE MYCOTOXINS

The gut microbiome refers to the diverse community of microorganisms living in the digestive tract, primarily in the intestines. These microorganisms play essential roles in digestion, nutrient absorption, and the synthesis of certain vitamins and hormones.

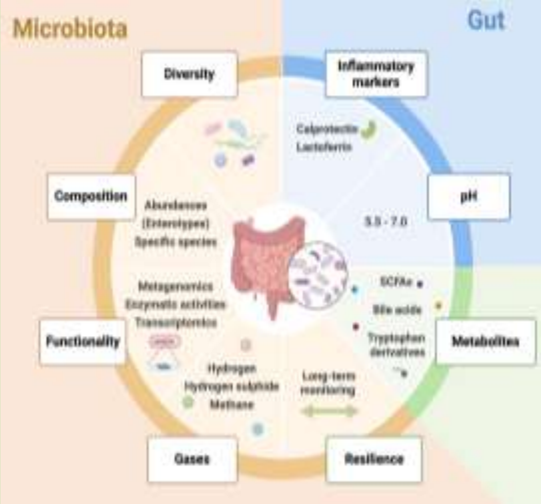

Figure 1. Potential markers of a healthy gut microbiota. A healthy gut microbiota is characterised by a diverse and balanced community of microorganisms that perform vital functions for the host. Several key markers have been proposed to assess these, including microbial diversity, composition (abundances, enterotypes, specific species), functionality (metagenomics, enzymatic activities, transcriptomics) and resilience (through long-term monitoring). Production of important metabolites like SCFAs, bile acids and tryptophan derivatives, as well as gases (hydrogen, hydrogen sulfide, methane), are potential indicators. Additionally, gut health indicators such as pH levels and the presence of inflammation markers (like calprotectin, lactoferrin) can be used for assessing overall gut health. SCFAs, short-chain fatty acids (from Van Hul et al., 2024).

HACCP CONTROL POINTS FOR MYCOTOXIN MANAGEMENT

The Hazard Analysis and Critical Control Points (HACCP) framework provides a systematic approach to identifying, evaluating, and controlling hazards in food production. When applied to mycotoxins, HACCP emphasizes prevention at critical stages rather than relying solely on end product testing.

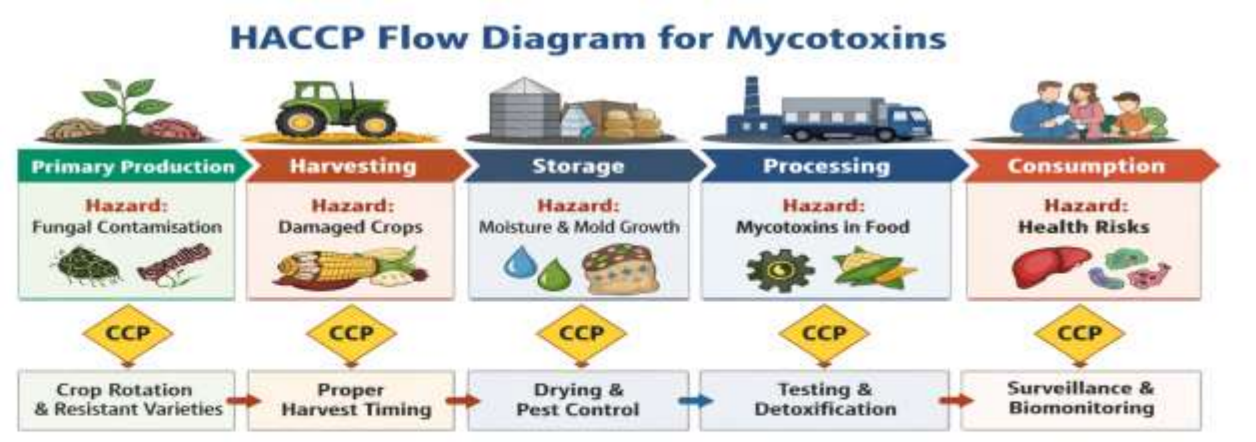

Figure 2. HACCP flow diagram for mycotoxin control in food systems

MICROBIOME BIOMARKERS IN FOOD SAFETY

Traditional monitoring, which focuses on detecting chemical residues such as aflatoxins or fumonisins in food products, microbiome biomarkers provide a biological readout of how these toxins affect host physiology even at low, chronic exposure levels.

One of the most widely studied indicators is microbial diversity. Healthy gut ecosystems are characterized by high richness and evenness, measured through indices such as Shannon and Simpson. Exposure to aflatoxin B_1 has been shown to reduce microbial diversity, weakening the resilience of the gut ecosystem and increasing susceptibility to opportunistic pathogens (Chałaśkiewicz et al., 2025).

Another critical set of biomarkers involves short-chain fatty acids (SCFAs), including acetate, propionate, and butyrate. These metabolites are produced by gut microbes during fiber fermentation and play essential roles in maintaining intestinal barrier integrity and modulating immune response

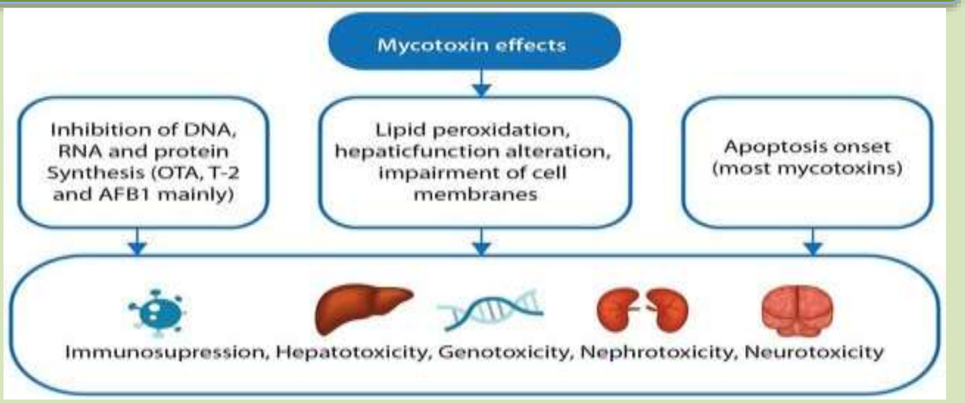

Figure 3. Major mechanisms of mycotoxin toxicity and their effects. Different mechanisms of mycotoxins can affect different organs and tissues in birds such as inhibition of protein synthesis, lipid peroxidation, hepatic function impairment, apoptosis modulation, among others. DNA, deoxyribonucleic acid; RNA, ribonucleic acid; OTA, ochratoxin; AFB1, aflatoxin B1 (from Gómez-Osorio et al., 2024).

CONCLUSION

The interplay between **foodborne mycotoxins** and the **gut microbiome** represents a critical frontier in modern food safety research. Mycotoxins such as aflatoxins, ochratoxin A, deoxynivalenol, fumonisins, and zearalenone exert not only direct toxicological effects but also profound influences on microbial composition, metabolism, and immune regulation. These interactions reshape the intestinal ecosystem, leading to dysbiosis, inflammation, and metabolic imbalance. Integrating microbiome-based indicators into the HACCP framework transforms food safety from a purely chemical surveillance system into a **biological risk-assessment model**.