IJAAR PUBLISHING®

American Research Journal of Contemporary Issues | ISSN: 3027-0189
Vol. 3, Issue 1 (2025) | www.ijaar.org

UNDERSTANDING THE BASICS AND EFFECTS OF AFLATOXINS ON THE ENVIRONMENT

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Abstract

Aflatoxins, toxic secondary metabolites produced by certain fungi, pose significant risks to human health, agriculture, and ecosystems. This review explores the origins, environmental distribution, and ecological impacts of aflatoxins, emphasizing their persistence in soil, water, and food chains. It also discusses strategies for mitigating their environmental effects, supported by recent research. Understanding aflatoxins' behavior in the environment is critical for developing sustainable solutions to minimize their ecological and societal harm.

Keywords: aflatoxins; secondary metabolites; human health; environmental distribution

Theophilus, S. M., Sunday, M., & Amoto, I. S. (2025). Understanding the Basics and Effects of Aflatoxins on the Environment. *American Research Journal of Contemporary Issues. 3*(1), 56-72. DOI: https://doi.org/10.5281/zenodo.16903875

1.0 Introduction

Aflatoxins are a group of naturally occurring mycotoxins produced primarily by certain strains of fungi, notably Aspergillus flavus and Aspergillus parasiticus. These toxins are highly toxic and carcinogenic compounds that contaminate a wide range of agricultural commodities, such as maize, peanuts, cottonseed, and tree nuts, particularly in warm and humid climates (Bennett & Klich, 2003). Aflatoxins pose significant risks to human and animal health, food security, and environmental sustainability due to their persistence in the environment and their ability to enter the food chain. This introduction provides a comprehensive overview of the basics of aflatoxins, their sources, environmental impacts, and mitigation strategies, with supporting tables and figures where applicable.

1.1 Basics of Aflatoxins

Aflatoxins are secondary metabolites produced by Aspergillus species under specific environmental conditions, including high temperatures (25–35°C) and humidity levels above 85% (Williams et al., 2004). The primary aflatoxins of concern are B1, B2, G1, and G2, with aflatoxin B1 (AFB1) being the most toxic and prevalent. These toxins are chemically stable, heat-resistant, and capable of persisting through food processing, making them a persistent environmental and health hazard (Wogan et al., 2012).

1.2 Sources of Aflatoxins

Aflatoxins contaminate crops during pre-harvest, harvest, and post-harvest stages. Key sources include:

1.2.1 Agricultural Crops

Maize, peanuts, rice, sorghum, and nuts are highly susceptible to aflatoxin contamination, especially in tropical and subtropical regions (Cotty & Jaime-Garcia, 2007).

1.2.2 Soil and Plant Debris

Aspergillus fungi thrive in soil and decaying plant material, serving as reservoirs for fungal spores that infect crops (Jaime-Garcia & Cotty, 2006).

1.2.3 Storage Conditions

Improper storage, such as high moisture and poor ventilation, promotes fungal growth and aflatoxin production in stored grains (Hell & Mutegi, 2011).

1.2.4 Animal Feed and Byproducts

Contaminated feed can lead to the accumulation of aflatoxin M1 (AFM1), a metabolite of AFB1, in milk and dairy products (Fink-Gremmels, 2008).

Table 1: Major Aflatoxins and Their Characteristics

Aflatoxin Type	Producing Fungi	Primary Crops Affected	Toxicity Level
Aflatoxin B1	A. flavus, A. parasiticus	Maize, peanuts, cottonseed	High (carcinogenic)
Aflatoxin B2	A. flavus, A. parasiticus	Maize, peanuts, tree nuts	Moderate
Aflatoxin G1	A. parasiticus	Peanuts, rice	Moderate
Aflatoxin G2	A. parasiticus	Peanuts, sorghum	Low
Aflatoxin M1	Metabolite in animals	Milk, dairy products	Moderate

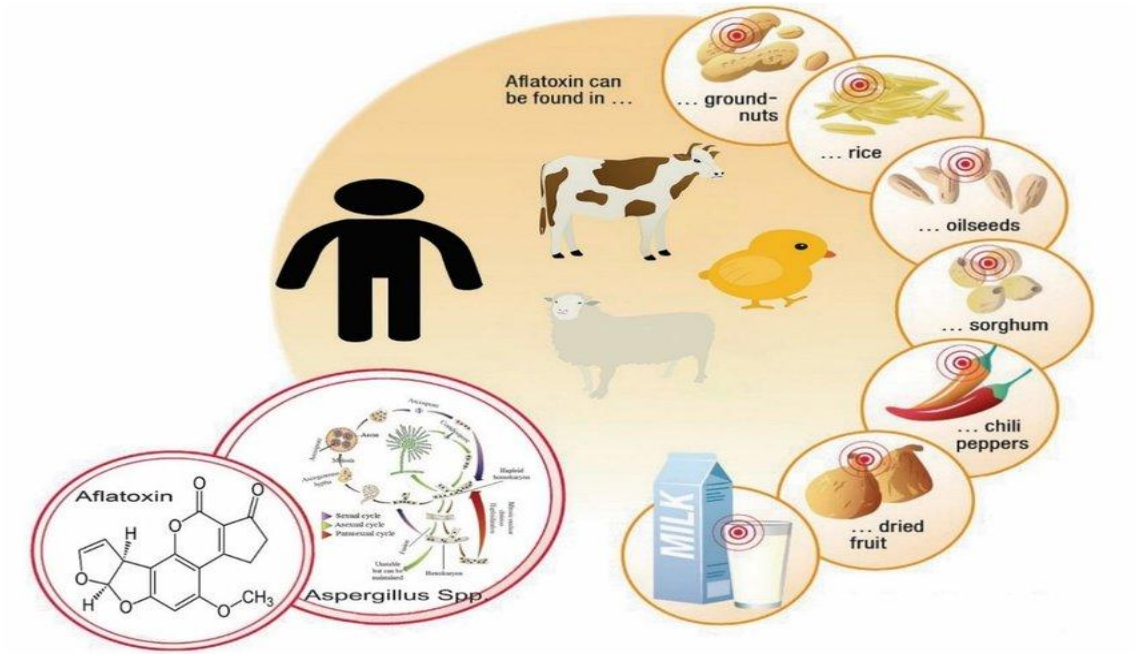
(Source: Adapted from Wogan et al., 2012)

1.3 Environmental Effects of Aflatoxins

Aflatoxins have far-reaching consequences for the environment, impacting ecosystems, agricultural systems, and biodiversity. Their persistence in soil, water, and food chains amplifies their environmental footprint.

1.4 Soil and Ecosystem Contamination

Aspergillus fungi are ubiquitous in soil, where they colonize organic matter and produce aflatoxins that can persist for extended periods. Aflatoxins in soil can: Contaminate groundwater through leaching, affecting aquatic ecosystems (Accinelli et al., 2008). Inhibit soil microbial activity, disrupting nutrient cycling and soil fertility (Angle, 1986). Affect non-target organisms, such as earthworms and beneficial insects, leading to ecological imbalances (Zablotowicz et al., 2000).



(Source: Iram et al., 2016).

Figure 1: The life cycle of Aspergillus and aflatoxins in food and feed

Figure 1. Showing the flow of aflatoxins from fungal growth in soil to crop contamination, animal consumption, and environmental re-entry through waste and runoff.

1.5 Agricultural Systems

Aflatoxin contamination reduces crop quality and yield, leading to significant economic losses. Contaminated crops are often unsuitable for human or animal consumption, resulting in food waste and increased pressure on agricultural land (Wu, 2015). Additionally: Farmers may resort to increased pesticide use to control fungal growth, contributing to chemical pollution (Cotty & Jaime-Garcia, 2007); and Contaminated crop residues used as mulch or compost can reintroduce aflatoxins into the soil, perpetuating the contamination cycle (Accinelli et al., 2008).

1.6 Bioaccumulation in Food Chains

Aflatoxins enter the food chain through contaminated crops and animal feed, leading to bioaccumulation in livestock and humans. For example: Aflatoxin M1 in milk results from dairy animals consuming AFB1-contaminated feed, posing risks to human health (Fink-Gremmels, 2008); and Wildlife consuming contaminated grains or plants may suffer from toxicity, affecting biodiversity (Zablotowicz et al., 2000).

1.7 Water Contamination

Runoff from contaminated fields can introduce aflatoxins into surface and groundwater, affecting aquatic organisms and drinking water quality. Studies have detected aflatoxins in water bodies near agricultural fields, highlighting their potential to disrupt aquatic ecosystems (Accinelli et al., 2008).

1.8 Health and Economic Implications

While the primary focus is environmental impact, aflatoxins also have indirect environmental consequences through their effects on human and animal health. Aflatoxin exposure is linked to liver cancer, immune suppression, and stunted growth in children (Wild & Gong, 2010). Economically, aflatoxin contamination leads to trade restrictions, as many countries enforce strict regulatory limits (e.g., 20 ppb for AFB1 in the U.S., 4 ppb in the EU), resulting in crop rejection and increased environmental waste (Wu, 2015).

2.0 Sources of Aflatoxins

Aflatoxins are primarily produced by fungi in the Aspergillus genus, with A. flavus and A. parasiticus being the most significant contributors. Other species, such as A. nomius, A. pseudotamarii, A. astellatus, A. venezuelensis, and A. olivicola, also produce aflatoxins but are less common (Jallow et al., 2021; Frisvad et al., 2004; Zalar et al., 2008). These fungi are ubiquitous in soil, decaying vegetation, and indoor environments, thriving in warm, humid climates, particularly in tropical and subtropical regions.

2.1 Sources of Aflatoxin Contamination

2.1.1 Agricultural Crops

Aflatoxins contaminate staple crops such as maize, peanuts, cottonseed, tree nuts, rice, wheat, barley, sorghum, and spices. Contamination can occur pre-harvest (during crop growth) or post-harvest (during storage and transportation).

2.1.2 Animal Feed

Contaminated feed can lead to secondary contamination in animal-derived products, such as aflatoxin M1 (AFM1) in milk, which is a metabolite of aflatoxin B1 (AFB1) (Jallow et al., 2021).

2.1.3 Fermented Foods

Traditional fermented foods in developing countries are vulnerable due to uncontrolled fermentation processes and poor storage conditions (Shukla et al., 2014).

2.1.4 Environmental Reservoirs

Soil, decaying organic matter, and indoor environments (e.g., poorly ventilated storage facilities) serve as reservoirs for aflatoxigenic fungi (Chen et al., 2016).

Table 2: Common Crops and Products Affected by Aflatoxin Contamination

Crop/Product	Aflatoxin Types	Primary Contamination Phase	Reference
Maize	AFB1, AFB2, AFG1, AFG2	Pre- and post-harvest	Temba et al., 2021
Peanuts	AFB1, AFB2	Pre- and post-harvest	Liu et al., 2016
Milk	AFM1	Secondary (animal feed)	Jallow et al., 2021
Spices	AFB1, AFG1	Post-harvest	El Darra et al., 2019
Rice	AFB1	Post-harvest	Jallow et al., 2021

2.2 Production of Aflatoxins

Aflatoxin production is a complex process influenced by fungal genetics, environmental conditions, and substrate characteristics. The major aflatoxins include B1, B2, G1, and G2, with AFB1 being the most toxic and prevalent. Aflatoxin M1 and M2 are hydroxylated metabolites found in animal products.

2.2.1 Biosynthesis Pathway

The biosynthesis of aflatoxins involves a complex pathway regulated by approximately 25-27 genes in the aflatoxin biosynthetic gene cluster (AF cluster). Key components include: Polyketide synthase (PKS) and non-ribosomal peptide synthetase (NRPS) enzymes, which assemble the carbon skeletons of aflatoxins; Transcription factors (aflR and aflJ) that regulate gene expression in response to environmental cues such as temperature, pH, and nutrient availability (Kumar et al., 2018); and Cytochrome P450 monooxygenases, which activate AFB1 into its toxic form, AFB1-8,9-epoxide, responsible for its carcinogenic effects (Benkerroum, 2020).

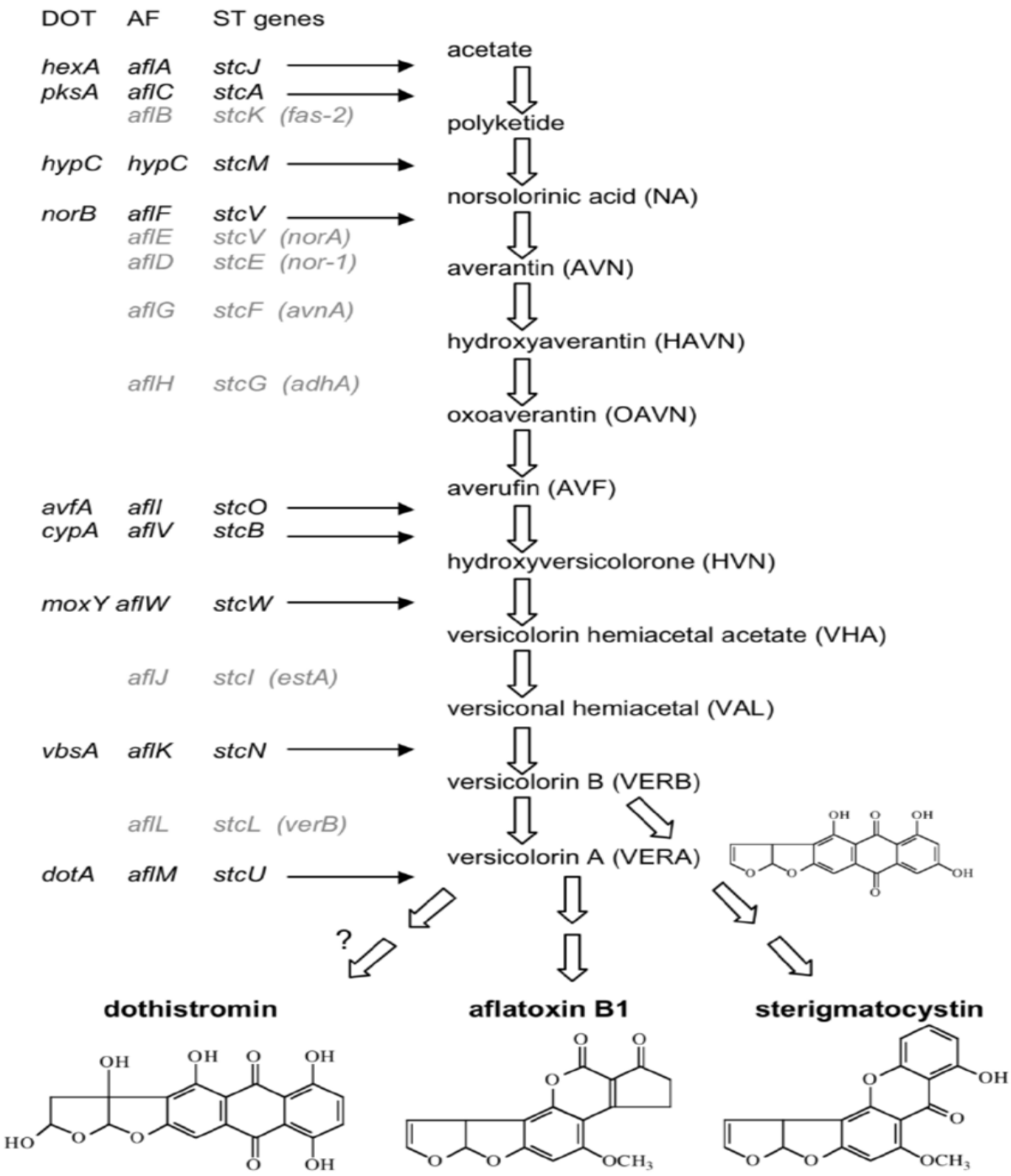


Figure 2: Simplified Aflatoxin Biosynthesis Pathway

Simplified biosynthetic pathway for aflatoxin (AF) and sterigmatocystin (ST) and predicted pathway for dothistromin (DOT) showing key intermediates and chemical structures of pathway products. Probable sites of action of the currently known dothistromin genes (left), and their AF and ST orthologs, are indicated. Some other biosynthetic genes expected to be present in D. septosporum are indicated in grey, with old AF gene names in parenthesis for clarification.

2.3 Environmental Factors Influencing Production

Rising temperatures, erratic rainfall, and increased CO2 levels (700–1000 ppm) stimulate aflatoxin production, particularly in temperate regions like the Mediterranean (Medina et al., 2014). Aflatoxin production is highly sensitive to environmental conditions, particularly:

2.3.1 Temperature

Optimal production occurs between 20–35°C, with AFB1 production peaking at 25–30°C (Schroeder & Hein, 1967).

2.3.2 Humidity/Water Activity

High humidity (40–89%) and water activity (0.90–0.99) promote fungal growth and toxin production (Villers, 2014).

2.3.3 Nutrient Availability

Lipid-rich substrates (e.g., corn oil) enhance aflatoxin production, while low sugar concentrations have minimal impact (Liu et al., 2016).

2.3.4 Pre- and Post-Harvest Factors

Drought stress, high temperatures, and pest damage increase crop susceptibility to fungal invasion (Cotty & Garcia, 2007). Poor storage conditions (e.g., high humidity, inadequate sealing) exacerbate contamination, leading to exponential fungal growth (Villers, 2014).

Table 3: Environmental Factors Affecting Aflatoxin Production

Factor	Optimal Range	Impact on Aflatoxin Production	Reference
Temperature	20–35°C	Peak AFB1 at 25–30°C	Schroeder & Hein, 1967
Water Activity	0.90–0.99	Promotes fungal growth	Villers, 2014
CO2 Levels	700–1000 ppm	Stimulates AFB1 production	Medina et al., 2014
Substrate Lipids	High lipid content	Increases toxin production	Liu et al., 2016

3.0 Effects of Aflatoxins on the Environment

Aflatoxins have significant environmental implications, affecting ecosystems, agriculture, and food security. Their persistence in soil, water, and food chains contributes to ecological and economic challenges.

3.1 Soil and Ecosystem Contamination

Aflatoxigenic fungi, such as A. flavus, are ubiquitous in soil, where they decompose organic matter and persist as spores. Contaminated crops release aflatoxins into the soil during harvesting or decomposition, creating a reservoir for future contamination (Chen et al., 2016).

Aflatoxins can persist in soil and water, affecting microbial communities and potentially disrupting nutrient cycling (Domsch et al., 2007).

3.2 Impact on Agriculture and Food Security

Aflatoxin contamination leads to significant crop losses, estimated at $225 million annually for maize and $25.8 million for peanuts in the U.S. alone (Jallow et al., 2021). Contaminated crops are often rejected for international trade due to strict regulatory limits (e.g., EU: 4 µg/kg for total aflatoxins; FDA: 20 µg/kg), exacerbating economic losses in developing

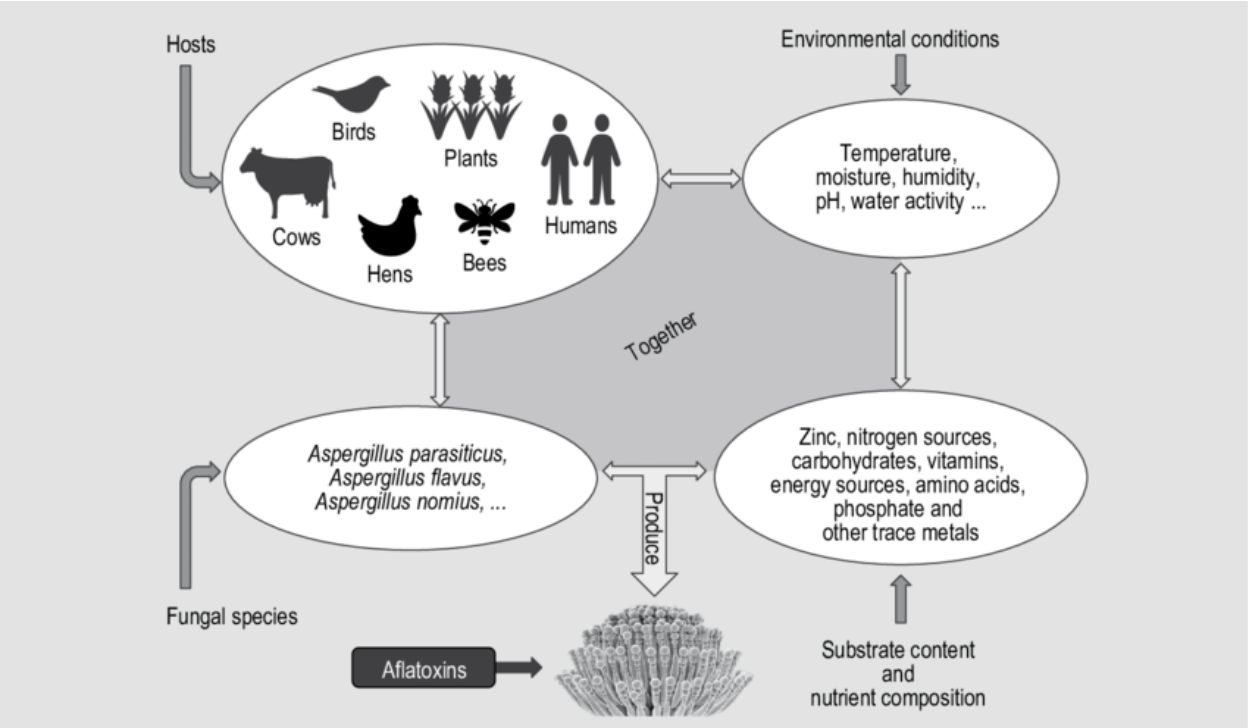
countries (Benkerroum, 2020). In Sub-Saharan Africa and Southeast Asia, aflatoxin contamination threatens food security by reducing the availability of safe staple foods (Warnatzsch et al., 2020).

3.3 Climate Change and Environmental Amplification

Climate change increases the risk of aflatoxin contamination by creating favorable conditions (higher temperatures, erratic rainfall, and droughts) for fungal growth (Battilani et al., 2016). Modeling studies predict a 50% increase in AFM1 in milk by 2030 in Eastern Europe due to climate-driven increases in AFB1 in animal feed (Van der Fels-Klerx et al., 2019). Elevated CO2 levels enhance AFB1 production, particularly under drought stress, posing challenges for temperate regions like Southern Europe (Medina et al., 2014).

3.4 Secondary Contamination in Food Chains

Aflatoxins enter the food chain through contaminated animal feed, leading to AFM1 in milk and dairy products, which persists due to its chemical stability (Jallow et al., 2021). Aquatic ecosystems may be affected by aflatoxin residues in runoff from contaminated fields, potentially impacting fish and other organisms (Kpodo et al., 1996).



(Source: Tumukunde, E., et al., 2020).

Figure 3: Environmental conditions vis-a-vis aflatoxins production

Figure 3: Show Environmental Impact of Aflatoxins Cycle (Fungi in soil → Contamination of crops → Aflatoxin release during harvest/storage → Soil and water contamination → Re-infection of crops). Climate Influence (Rising temperatures and humidity → Increased fungal growth → Higher aflatoxin production → Greater environmental persistence).

4.0 Human and Agricultural Implications

4.1 Human Health Implications

Aflatoxins pose severe risks to human health due to their toxicity, carcinogenicity, and widespread occurrence in food.

4.1.1 Acute Toxicity (Aflatoxicosis)

Acute exposure to high levels of aflatoxins causes aflatoxicosis, characterized by jaundice, abdominal pain, vomiting, and liver failure. Severe cases can be fatal. In 2004–2005, an outbreak in Kenya linked to contaminated maize resulted in 317 cases and 125 deaths (Lewis et al., 2005). AFB1's reactive epoxide binds to DNA, forming adducts that disrupt cellular processes and cause acute liver damage (Benkerroum, 2020).

4.1.2. Chronic Toxicity and Carcinogenicity

AFB1 is a potent liver carcinogen, increasing Hepatocellular Carcinoma (HCC) risk, particularly in individuals with hepatitis B or C. In high-risk regions like Sub-Saharan Africa and Southeast Asia, aflatoxin exposure contributes to 4.6–28.2% of HCC cases (Liu & Wu, 2010). Co-exposure to aflatoxins and hepatitis B virus (HBV) increases HCC risk up to 60-fold due to mutations in the p53 tumor suppressor gene (IARC, 2012). Chronic exposure is linked to immunosuppression, stunting in children, and reduced nutrient absorption (Jallow et al., 2021).

4.1.3 Exposure Pathways

Consumption of contaminated crops (e.g., maize, peanuts) is the primary route. In developing countries, dietary exposure can exceed 1 µg/kg body weight/day, far above safe levels (WHO, 2018). AFM1 in milk and dairy products poses risks, especially for infants and young children (Van der Fels-Klerx et al., 2019). Farmers and food processors handling contaminated crops may inhale aflatoxin-containing dust (Viegas et al., 2018).

Table 4: Human Health Effects of Aflatoxin Exposure

Exposure Type	Health Effect	Symptoms/Outcomes	Reference
Acute	Aflatoxicosis	Jaundice, liver failure, death	Lewis et al., 2005
Chronic	Hepatocellular carcinoma	Liver cancer, p53 mutations	Liu & Wu, 2010
Chronic	Immunosuppression	Increased infection risk	Jallow et al., 2021
Chronic	Child stunting	Growth impairment	WHO, 2018
Secondary	AFM1 exposure	Developmental risks in infants	Van der Fels-Klerx et al., 2019

4.2 Agricultural Implications

Aflatoxins have profound economic and food security impacts on agriculture, particularly in tropical and subtropical regions.

Aflatoxin contamination leads to significant yield losses, with global estimates suggesting 25% of crops are affected (Jallow et al., 2021). In the U.S., annual losses for maize and peanuts are estimated at $225 million and $25.8 million, respectively (Robens & Cardwell, 2003).

Strict regulatory limits (e.g., EU: 4 µg/kg total aflatoxins; FDA: 20 µg/kg) result in rejection of contaminated exports, disproportionately affecting developing countries (Benkerroum, 2020). In Africa, aflatoxin-related trade losses are estimated at $670 million annually, impacting economies reliant on agricultural exports (Jallow et al., 2021).

Contamination reduces the availability of safe staple foods, exacerbating hunger in regions like Sub-Saharan Africa, where maize and peanuts are dietary staples (Warnatzsch et al., 2020). Contaminated crops are often diverted to animal feed, leading to secondary contamination (AFM1 in milk), further reducing food safety (Van der Fels-Klerx et al., 2019).

Animals fed contaminated feed exhibit reduced growth, immunosuppression, and lower productivity. AFM1 residues in milk pose additional risks to human consumers (Jallow et al., 2021). Poultry and cattle are particularly susceptible, with AFB1 causing liver damage and reduced egg/milk production (Cotty & Garcia, 2007).

Table 5: Agricultural Impacts of Aflatoxin Contamination

Impact Area	Effect	Economic/Social Cost	Reference
Crop Losses	Contaminated maize, peanuts	$225M (maize), $25.8M (peanuts) in U.S.	Robens & Cardwell, 2003
Trade	Export rejections	$670M annually in Africa	Jallow et al., 2021
Food Security	Reduced safe food supply	Increased hunger in Sub-Saharan Africa	Warnatzsch et al., 2020
Livestock	Reduced productivity, AFM1 in milk	Lower yields, human health risks	Cotty & Garcia, 2007

4.3 Environmental Effects of Aflatoxins

Aflatoxins persist in the environment, affecting ecosystems and amplifying agricultural and human health challenges.

4.3.1 Soil and Water Contamination:

Aflatoxigenic fungi (A. flavus, A. parasiticus) are soilborne, and aflatoxins released from contaminated crops persist in soil, creating reservoirs for future infections (Chen et al., 2016).

Runoff from contaminated fields can introduce aflatoxins into water bodies, potentially affecting aquatic organisms like fish (Kpodo et al., 1996).

4.3.2 Ecosystem Disruption:

Aflatoxins may alter soil microbial communities, disrupting nutrient cycling and soil health (Domsch et al., 2007).

Contaminated crops and feed affect wildlife and livestock, potentially reducing biodiversity in affected ecosystems (Jallow et al., 2021).

4.3.3 Climate Change Amplification:

Rising temperatures (20–35°C), erratic rainfall, and elevated CO2 levels (700–1000 ppm) enhance fungal growth and aflatoxin production, increasing contamination risks in temperate regions like Southern Europe (Battilani et al., 2016; Medina et al., 2014).

Modeling predicts a 50% increase in AFM1 in milk by 2030 in Eastern Europe due to climate-driven AFB1 increases in feed (Van der Fels-Klerx et al., 2019).

5.0 Mitigation and Control Strategies

5.1 Mitigation Strategies

Effective management of aflatoxins requires integrated approaches targeting pre-harvest, harvest, and post-harvest stages. Below are evidence-based strategies:

5.1.1 Pre-Harvest Strategies

Use resistant crop varieties, such as aflatoxin-resistant maize hybrids (e.g., TELA maize). Genetic engineering to enhance resistance to fungal infection (Brown et al., 2013);

Implement crop rotation and intercropping to reduce fungal inoculum in soil. Maintain optimal irrigation to avoid drought stress, which increases aflatoxin production;

Apply atoxigenic strains of Aspergillus flavus (e.g., Aflasafe) to outcompete toxigenic strains, reducing aflatoxin levels by up to 90% (Bandyopadhyay et al., 2016). Example: Aflasafe has been successfully implemented in Nigeria and Kenya.

5.1.2 Harvest and Post-Harvest Strategies

Harvest crops at optimal maturity to minimize fungal infection. Avoid physical damage during harvesting to reduce fungal entry points.

Dry crops to a moisture content below 10% to inhibit fungal growth. Use hermetic storage bags or silos to maintain low humidity and prevent contamination (Hell et al., 2010).

Sort and remove visibly contaminated grains to reduce aflatoxin levels. Use ammonia-based treatments or ozonation to degrade aflatoxins in stored grains (Samarajeewa et al., 1990).

5.1.3 Environmental Management

Incinerate or compost contaminated crop residues under controlled conditions to prevent environmental spread. Treat livestock waste to degrade aflatoxins before disposal.

Implement regular testing of crops and soil for aflatoxin levels using ELISA or HPLC methods. Enforce regulatory limits (e.g., FDA's 20 ppb limit for aflatoxins in food) to minimize environmental and health risks (FDA, 2020).

5.1.4 Education and Awareness

Train farmers on best practices for aflatoxin prevention, including proper storage and biocontrol application. Raise consumer awareness about safe food handling to reduce exposure (Waliyar et al., 2015).

Table 6: Summary of Mitigation Strategies

Stage	Strategy	Effectiveness	Reference
Pre-Harvest	Biocontrol (Aflasafe)	80–90% reduction in aflatoxins	Bandyopadhyay et al. (2016)
Harvest	Timely harvesting	Reduces fungal infection	Hell et al. (2010)
Post-Harvest	Hermetic storage	Prevents fungal growth	Hell et al. (2010)
Environmental	Controlled waste disposal	Minimizes soil/water contamination	Accinelli et al. (2016)

5.2 Challenges and Future Directions

5.2.1 Challenges

High costs of biocontrol agents and advanced storage systems limit adoption in low-income regions. Climate change exacerbates aflatoxin production due to increased temperatures and erratic rainfall. Lack of awareness among smallholder farmers hinders implementation of best practices.

5.3 Future Directions

Develop cost-effective biocontrol methods and resistant crop varieties. Leverage precision agriculture technologies (e.g., IoT sensors) to monitor environmental conditions and predict aflatoxin risks. Strengthen global regulations and surveillance systems to control aflatoxin spread.

Conclusion

Aflatoxins, produced by Aspergillus species, are a global concern due to their widespread contamination of crops and their persistence in the environment. Aflatoxins pose significant threats to human health, agriculture, and the environment. Their carcinogenic and toxic effects cause acute and chronic health issues, particularly in developing countries, while agricultural losses and trade restrictions undermine food security and economic stability. Environmental factors such as temperature, humidity, and nutrient availability significantly influence their production, with climate change amplifying risks. The environmental impacts include soil and water contamination, agricultural losses, and food chain disruptions. Effective management requires integrated approaches, including biocontrol, improved storage, and robust detection methods. Continued research into climate-resilient crops and advanced sensing technologies is critical to mitigate the environmental and health challenges posed by aflatoxins.

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