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Aflatoxin risk in the era of climatic change-a comprehensive review

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Abstract

This review highlights the major influence that both climate change and aflatoxin contamination have on global food safety as it examines their complex relationship. Fungi such as *Aspergillus flavus* produce aflatoxins, which can seriously harm one's health by compromising the immune system and causing chronic disorders. The review looks at how temperature and humidity affect the production of aflatoxin. The evaluation of current models emphasizes the necessity for novel strategies and up-to-date climatic data. The changing climatic conditions are taken into consideration while discussing regulatory frameworks and international standards. Additionally, the paper explores cutting-edge sensing technologies for improved surveillance of aflatoxin contamination. Molecular markers and resistance characteristics are two areas of future investigation. In view of a changing climate, the conclusion emphasizes the continued difficulties in creating crops that are climate resilient and calls for cooperation in addressing aflatoxin problems.

Keywords Aflatoxins, Climate change, Models, Technologies, Climate resilient

Introduction

Crop and food contamination with aflatoxin is a worldwide problem. It compromises the safety of food and animal feed and damages the economies of agricultural sectors and geographical areas where it is found. Aflatoxins are a group of four mycotoxins (B1, B2, G1, and G2) predominantly produced by the fungus *Aspergillus flavus* and *Aspergillus parasiticus*, which are closely related (Yin et al. 2008). For crops, contamination with aflatoxin before harvesting is a prevalent problem. Furthermore, *A. flavus* continues to be a threat even after harvest, causing grain storage deterioration (St. Leger et al. 2000).

Aflatoxin contamination is a worldwide problem that affects a wide range of agricultural goods rather than being exclusive to a particular area or crop. Corn (maize) and peanuts (groundnuts) are two of the crops most vulnerable to aflatoxin contamination (Williams et al. 2004).

Most A. *parasiticus* strains can produce all four main aflatoxins (AFB1, AFB2, AFG1, and AFG2), toxic A. *flavus* strains often only produce AFB1 and AFB2. The capacity of these species to produce aflatoxins as well as other mycotoxins like ochratoxins has been highlighted by recent research that have deepened understanding of their taxonomy and mycotoxin production (Frisvad et al. 2019) (Table 1).

Almost 70% population of the world are exposed to the threats of aflatoxins including 4.5 billion people living in Asia and Africa (Umar et al. 2023). Aflatoxin contamination is becoming a big problem in Asia, especially in nations like China and India where rice and spices like pepper and chilli are frequently contaminated (Benkerroum 2020). Aflatoxin contamination in maize has also been detected in the United States, particularly under drought conditions that damage crops and encourage fungus growth (Cotty and Jaime-Garcia 2007). *A. flavus* can cause maize to develop ear rot when the weather is

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Table 1 Table showing major types of aflatoxins and their source of production

Major Aflatoxins	Source	References
Aflatoxin B1 (AFB1) and B2 (AFB2)	*Aspergillus flavus*, *A. parasiticus*	Fouad et al. (2019)
Aflatoxin G1 (AFG1) and G2 (AFG2)	*Aspergillus flavus*, *A. parasiticus*	Ting et al. (2020)
Aflatoxin M1 (AFM1)	Metabolite of AFB1 in animals and human (in milk)	Prandini et al. (2009)
Aflatoxin M2 (AFM2)	Metabolite of AFB2 in cattle milk	Antunović et al. (2022)
Aflatoxicol	Metabolite of AFB1 and AFM1	Zhang et al. (2023)
Aflatoxin Q1	Major metabolite of B1 in liver (In-vitro)	Popescu et al. (2022)

favourable for it to do so, which can generate economic losses for farmers (Richard et al. 2003).

Aflatoxin levels have also grown in peanut harvests in the Southeast of the United States, which presents problems for both local consumption and foreign commerce. Aflatoxin poisoning of tree nuts, such pistachios and almonds, has also increased in California, affecting one of the biggest agricultural industries in the country. Temperature and humidity patterns have changed in certain areas, which has made it easier for Aspergillus species to proliferate produce aflatoxins (Dorner 2008; Medina et al. 2014).

Food safety and the risk of aflatoxin are both significantly impacted by climate change. The significant global costs of contaminated food and feed have already been extensively studied, and these costs are expected to rise because of the increased frequency and severity of climate-related extremes. A complex interplay of factors that can alter the features of fungi, the environment, and their hosts is brought about by climate change, which acts as a catalyst (Hope and Magan 2003). Aflatoxins produced by *A. flavus* are destined to raise additional issues in this situation.

Climate change and agricultural methods have a substantial impact on the frequency and severity of aflatoxin contamination in crops. The study done by Massomo (2020) highlights how climate change-related fluctuations in temperature, humidity, and precipitation patterns foster the growth and production of aflatoxins by Aspergillus species (Massomo 2020).

Aflatoxin contamination and its consequences

Chronic illnesses, with cancer being one of the frequent and most severe outcomes, can result from repeated, lifelong exposure to low amounts of aflatoxins. Meanwhile, acute aflatoxicosis is known to be caused by a high amount of aflatoxin exposure that takes place over a brief time. Aflatoxin exposure through diet is traditionally linked to primary liver cancer (HCC and bile duct hyperplasia), however these mycotoxins have also been linked to the emergence of cancer in a number of other organs, including the kidneys, pancreas, bladder, bones, and more (McGlynn and London 2005). Aflatoxin exposure by inhalation and direct skin contact has been linked to occupational malignancies of the lungs and skin (Kelly et al. 1997).

Aside from these major health problems, persistent exposure to aflatoxins can also have an adverse impact on the immune system and have teratogenic, mutagenic, cytotoxic, and estrogenic effects on mammals (Klvana and Bren 2019).

There is significant aflatoxin contamination in the food crops as well as other crops of the various regions. The most typical sources of these toxins include common foods like corn and rice, as well as vital ingredients in food preparation like spices. They also affect nuts, dried fruits, and even figs, posing a serious danger to the security of major food and feed products (Martinez-Miranda et al. 2019).

Aflatoxin contamination in various regions through climate change

Climate variations also have an impact on contamination as they alter the host crops' susceptibility to Aspergillus fungi, which produce aflatoxin. These modifications are associated with variations in crop growth and fluctuations in the population of insects that produce wounds, which serve as way of entrance of Aspergillus.

A study supported by EFSA predicts that the danger of aflatoxin contamination in maize would increase due to climate change. An extensive evaluation of the literature revealed the need for interdisciplinary methods and more study to comprehend the relationship between mycotoxin co-occurrence and climate change (Leggieri et al. 2021).

Aflatoxin contamination is increasing in continental regions in the middle latitudes (40°–55° North) because of global warming and rising greenhouse gas emissions. The primary fungi, *Aspergillus flavus* and *A. parasiticus*, are more likely to thrive and produce aflatoxin in response to rising temperatures, endangering the health of people, animals, and plants. *A. flavus* multiplies best

at temperatures of about 28 °C, which increases aflatoxin contamination (Kanyi 2018).

Contamination with aflatoxin is a problem in both wet, warm settings and irrigated desert areas. Drought conditions in temperate zones might make contamination worse (Cotty and Jaime-García 2007). Aflatoxin pollution is a result of a country's economic standing as well as climatic conditions, which affects storage conditions that encourage the growth of mould, particularly in Southeast Asia and Sub-Saharan Africa (Benkerroum 2019). There is no discernible trend of improvement despite efforts, necessitating worldwide risk assessments and regulatory changes for efficient public health protection.

A modelling study estimates that, despite geographic variations and the inactivation of causative fungi in certain southern counties under extremely high temperatures, over 89.5% of corn-growing counties in 15 US states, including the Corn Belt, will experience increased aflatoxin contamination due to climate change by 2031–2040 (Yu et al. 2022).

In Pakistan, unsafe levels of aflatoxin contamination were found in chilies of Punjab region. The levels of aflatoxin were found to be higher in 23% of whole chili pods and 30% of powdered chilies than that of the EU's acceptable standards which is 4µg. High levels of aflatoxin are not only linked to health risks for humans but also affect this region's chili exports (Iqbal et al. 2011). It is imperative to monitor ongoing changes in the climate to lessen health risks and maintain agricultural exports.

A modelling technique used to simulate several temperature scenarios (+2 °C and +5 °C) indicated that there is a greater chance that aflatoxin B1 may become a serious problem for food safety, especially in Southern European nations. The likelihood of aflatoxin contamination is now low in key maize-cultivating regions, but the +2 °C scenario might further raise the risk (Battilani et al. 2016).

Van der Fels-Klerx et al. (2019) focused on Eastern European maize imported for Dutch dairy cow feed, utilizing three climate models, five carryover models, and an AFB1 prediction model. According to the research, milk may have 50% more AFM1 by 2030; however, this might vary based on the environment other carryover scenarios. This innovative prediction tool, which is adaptable enough to take into account other mycotoxins or production chains, may be used by policymakers to assess the effect of climate change on aflatoxin contamination in the dairy production chain (Van der Fels-Klerx et al. 2019).

Evaluation of the prevalence of aflatoxin by analysing 2494 peanut samples from 2010 to 2013 from China's main peanut production regions was done, the provinces of Liaoning, Henan, Sichuan, and Guangdong was subject of observation under this study. A month prior to harvest, there was a substantial association seen between aflatoxin levels and meteorological conditions. The climate most favorable for high levels of aflatoxin contamination is defined as having little to no precipitation, an average temperature of around 23 °C, a minimum temperature of about 20 °C, and a maximum temperature of about 29 °C (Wu et al. 2016). The Aspergillus fungi, which produces aflatoxins, grows best in an environment that is facilitated by certain external conditions.

A study investigated the association between AFB1 content and weather during the 2013 harvest season using maize samples from several agroecological zones in Kenya and Tanzania. The incidence of AFB1 ranged from 0 to 100%, averaging 29.4%, and one sample had values as high as 6075 µg/kg. This is significantly higher compared to the aflatoxin tolerable limits of 10 µg/kg in East Africa and 4 µg/kg in the EU. The results demonstrated the impact of high temperatures and little precipitation during the early stages of maturation on aflatoxin contamination, allowing risk maps to be created for the two nations (Temba et al. 2021).

Impact of environmental conditions on aflatoxin production

The change in climate has inevitable effects on aflatoxin production increasing risks of harms to animal and human life (Valencia-Quintana et al. 2020). Climate may have direct as well as indirect effects on aflatoxin proliferation. Both temperature and humidity increase may directly affect the aflatoxin production by providing favourable conditions for the fungi to proliferate. Climate may also have an indirect effect which causes wounds in plant via animals (Cotty and Garcia 2007).

The formation of aflatoxin by four isolates on various substrates at temperatures ranging from 10 to 40 °C was investigated in 1976. Within the first 10 days following inoculation, aflatoxin production was at its highest between 20 and 35 °C and at its lowest between 10 and 40 °C. Aflatoxin production and accumulation increased more quickly at higher temperatures, and at lower temperatures, a bigger proportion of aflatoxin G was produced and processed more quickly than aflatoxin B (Schroeder and Hein 1967).

Another study done by Sanders (1968) found that a mixture of environmental conditions could prevent the growth of fungi and the generation of aflatoxin. The effect of temperature, relative humidity (RH), and carbon dioxide (CO_2) on *Aspergillus flavus* in peanuts was examined in the study. It was discovered that a mixture of 20% CO_2 at 17 °C and 60%–40% CO_2 at 25 °C prevented the growth of fungi and the generation of aflatoxin at about 86% RH. As RH dropped, levels of aflatoxin and free fatty acids (FFA) dropped as well. Furthermore, the generation

of aflatoxin and FFA was reduced in response to both increased CO_2 concentration and decreased temperature, demonstrating the complex interplay between these variables in affecting *A. flavus* behaviour in peanuts (Sanders et al. 1968).

The production of aflatoxin by *Aspergillus flavus* and *Aspergillus parasiticus* on maize seeds was examined at various water activity (wa) levels (0.90, 0.95, and 0.98), as well as temperatures (25 °C, 30 °C, and 35 °C). Aflatoxin synthesis was also improved by cycling *A. flavus* between 25 and 35 degrees Celsius as opposed to continuous incubation at either temperature (Faraj et al. 1991).

The effects of temperature and water activity on *Aspergillus flavus* growth and aflatoxin production on peanut meal were examined by Mahror et al. (2020). According to their researh, 30 °C and high-water activity levels (0.98 aw) were the ideal temperatures for both fungal growth and aflatoxin synthesis. The fungi flourished fastest and produced the most aflatoxins under these circumstances, emphasizing how crucial it is to regulate moisture and temperature in order to reduce aflatoxin contamination in peanuts that have been kept (Mahror et al. 2020).

The study looked at the storage conditions for *Atractylodis rhizoma* and determined that the ideal conditions were below 20 °C and below 85% relative humidity. These circumstances effectively avoided the production of aflatoxin, providing helpful advice for maintaining product quality and safety (Liu et al. 2021a, b).

The incidence of aflatoxin in maize has been greatly impacted by climate change, as evidenced by warming patterns in Serbia and Croatia between 2018 and 2021. With 84% in Serbia and 40% in Croatia, the year 2021—which was marked by hot, dry weather—saw the greatest occurrence of aflatoxins in maize samples in both countries. This emphasizes how the region's aflatoxin contamination is affected by the climate (Pleadin et al. 2023).

Aflatoxin risk assessment in a changing climate

The problem of aflatoxin is predicted to worsen due to climate change, since elevated temperatures and modified precipitation patterns would probably foster an environment more conducive to the growth of fungi and the production of toxins. Aflatoxin exposure is becoming more likely, which emphasizes the need for effective risk assessment techniques and methods to safeguard the public's health.

1. **Mechanistic model**

   Mechanistic models are useful for predicting aflatoxin risk because they incorporate data on aflatoxin occurrences and a thorough understanding of the biophysical agricultural system. Several models, such as AFLA-maize, have been created to evaluate the risk of aflatoxin in the context of future climate scenarios. Applications like predictive modelling of aflatoxin contamination and climate-smart agricultural practices in places like Malawi, where it is predicted that climate change would affect maize growing seasons and increase exposure to aflatoxin, emphasize how crucial these models are for identifying and reducing new risks. The incorporation of mechanistic models into risk assessments is becoming increasingly necessary as climate-induced changes escalate (Nji et al. 2022).

   With temperature, relative humidity, and precipitation as inputs, it can predict aflatoxin contamination and crop phenology with accuracy. The effectiveness of the model has been demonstrated with pistachios using the AFLAPistachio framework, showcasing its versatility for various crop types (Kaminiaris et al. 2020).

   Compared to empirical models, mechanistic models like AFLA-maize show better extrapolation capabilities to new temporal or spatial constraints, potentially opening applications across a variety of geographic regions. The intricacies of cropping systems, such as soil type and cultivar, which are frequently left out of traditional mechanistic models, are being addressed by hybrid models (Bayer et al. 2023).

2. **Empirical model**

   The application of empirical models—which were first created for areas like Europe and Australia—to Sub-Saharan Africa is growing. However, the lack of georeferenced recalibration data limits their usefulness. Machine learning and other multivariate techniques are useful in overcoming this limitation since they can capture complex non-linear correlations between the frequency of aflatoxin and geospatial data (Liu et al. 2021a, b).

   The model of aflatoxin risk that is linked into the Agricultural Production Systems Simulator (APSIM) framework is one of the most well-known models. This empirical model, which was first created for peanuts in Australia, showed great prediction power, accounting for 95% of the variation in aflatoxin levels that were recorded (Chauhan 2010).

3. **Limitations for utility of these models**

   Extending predictive aflatoxin risk models to other countries during the production and postharvest stages presents both opportunities and challenges.

Two major obstacles are the lack of available data and the requirement to conform to regional farming methods, which necessitates large-scale data gathering (Keller et al. 2022).

Novel modelling strategies are required to overcome constraints in real-time climate data. Parallel developments in mobile decision support platforms and public and private extension services are needed to remove barriers to information access. It is imperative to prioritize the integration of model results into community development plans through capacity-building and raising awareness. Aflatoxin risk models can be effectively implemented in Sub-Saharan Africa (SSA) with the help of the establishment of financial incentive programs and the strengthening of extension service capabilities (Schreurs et al. 2019).

Regulatory frameworks and climate change considerations

Regulatory frameworks are necessary in order to stop aflatoxin contamination, protect the public's health, and advance global commerce, Aflatoxin regulations must take climate change-related aspects into account because they are causing new difficulties to arise. To guarantee that existing regulatory systems continue to be successful in the face of shifting environmental conditions, models that forecast how climate change will affect aflatoxin levels can be incorporated into them.

International agreements and standards

For the protection of consumers from the harms of aflatoxins agreements and standards have been developed worldwide (Van Egmond and Jonker 2002). Effective control of aflatoxin contamination is guided by important international organizations that have set rules and standards. Most important agreements and standards are enlisted below:

a. **Codex Alimentarius Commission (CAC):** The CAC, FAO/WHO joint committee, establishes maximum permitted levels (MPLs) of aflatoxins in different food products (FAO and WHO 2010).
b. **European Union (EU):** The EU has put in place extensive laws for aflatoxin management that include MPLs, sampling schedules, testing techniques, and control measures (European Commission 2018).
c. **United States Food and Drug Administration (FDA):** The FDA provides advice on efficient control methods and sets advisory thresholds for aflatoxins in a variety of food commodities (US Food and Drug Administration 2023).

Aflatoxin regulations and climate change

Regulations must take climate change into account in order to minimize aflatoxin risk in a changing climate. Regulations pertaining to aflatoxin can take many different forms, such as defining the maximum levels that are acceptable and using predictive models. Because of changes in temperature and precipitation patterns that promote fungal growth and the development of toxins, it is anticipated that climate change would worsen the contamination caused by aflatoxin (Faraj et al. 1991).

A comprehensive strategy considering the effects of climate change on aflatoxin contamination is needed to incorporate climate change into aflatoxin laws. To create efficient regulatory frameworks that address the issues posed by climate change on aflatoxin contamination in food and feed, this entails utilizing predictive models and risk assessment tools.

The specified level of protection determines how well the present aflatoxin regulation standards protect the public's health. Most countries fail to achieve the target of preventing a 1/100,000 rise in hepatocellular carcinoma (HCC) incidence over a lifetime, even though European countries have stringent regulations in place (Wu and Khlangwiset 2010). But most regulatory requirements are sufficient if the acceptable threshold is a 1/10,000 increase in HCC incidence; the exceptions are in Peru and Kenya because of higher rates of hepatitis B virus (HBV) and higher maize consumption (Wu et al. 2013). Standards may not always match actual contamination levels, and inadequacies in enforcement and surveillance have an impact on effectiveness. The dynamics of international trade also have an impact on the quality of products between countries with different regulatory frameworks (Wu and Guclu 2012).

Future strategies for managing aflatoxin contamination

Not much attention has been paid to the practicality of addressing aflatoxin contamination in the context of climate change. Based on the challenges faced, these strategies can play a pivotal role in adjusting the aflatoxin risk due to climate change.

a. **Climate-resilient agricultural practices**

By reducing crop stress and reducing possibilities for fungal growth, climate-resilient agricultural techniques are essential for reducing aflatoxin contamination (Cary et al. 2011). These include cultivating crop varieties resistant to drought, improving storage practices including airtight storage and appropriate drying techniques to reduce moisture content, and putting integrated pest management (IPM) plans into

action. These tactics give natural pest management techniques precedence over chemical pesticides, improving plant ecosystem health and reducing the possibility of aflatoxin contamination (Ortega-Beltran and Bandyopadhyay 2021).

b. **Climate based aflatoxin risk assessment**
Identifying areas and crops at high risk of contamination under future climatic scenarios requires incorporating climate forecasts into aflatoxin risk assessments. We may build plans that are relevant to the area and prioritize locations for preventive measures by knowing the particular climate variables that facilitate aflatoxin formation (Matumba et al. 2014).

c. **Regulations based on dynamic risk assessment**
A more adaptable and responsive strategy to aflatoxin management can be achieved by creating dynamic rules that modify maximum permitted levels (MPLs) or control measures depending on real-time climate data and aflatoxin monitoring findings (Stoloff et al. 1991). The effects of extreme weather and shifting climatic trends on aflatoxin contamination levels can be lessened with the use of this dynamic strategy.

d. **Strengthening Surveillance and Monitoring**
Considering climate change, it is imperative to manage aflatoxin contamination by strengthening surveillance and monitoring systems. Early detection technologies provide important insights into the dynamics of contamination and aid in early identification, well-informed decision-making, and resource allocation (Yao et al. 2015). The information gathered directs research activities, facilitating the creation of pre-emptive plans and focused initiatives to effectively reduce aflatoxin risks. An all-encompassing surveillance strategy helps build a strong foundation for aflatoxin control.

e. **Awareness and education**
It has become imperative to educate and raise awareness among stakeholders, including farmers, food processors, and consumers, to reduce the hazards associated with aflatoxin. Reducing contamination is aided by food processors' education on aflatoxin detection and mitigation as well as farmer education on good agricultural practices. Encouraging safe eating habits and educating consumers about aflatoxin warning indicators improves public health protection (Jallow et al. 2022).

f. **Technological Advances in Aflatoxin Detection in a Changing Climate**
As potential risks of aflatoxin contamination increase due to climate change, the necessity for accurate, dependable, and effective detection techniques increases. Here are the cutting-edge technologies that are transforming the detection of aflatoxin.

Table 2 Enlisting different emerging sensing and monitoring technologies used for aflatoxin detection

Emerging sensing and monitoring technologies
1. Enzyme-free catalytic DNA circuit
2. Modular separation-based fiber-optic sensors
3. Aptamer based detection
4. Ultra-sensitive magnetic relaxation sensing
5. Highly-Sensitive Molecularly-Imprinted Electrochemical Sensor
6. Liquid crystal-based immunosensor
7. Amplified π-shape electrochemical aptasensor
8. SPR nanosensor with gold nanoparticles
9. SERS aptasensor

Emerging sensing and monitoring technologies

When it comes to risk assessment and large-scale aflatoxin monitoring, emerging sensing technologies are unmatched. By utilizing information obtained through non-contact methods, these instruments provide prompt and accurate measures to alleviate fungal contamination. Table 2 lists the major emerging sensing and monitoring technologies in use to determine aflatoxin contamination.

1. **Modular separation-based fibre-optic sensors**

This sensor combines the sensitivity of fibre-optic-based laser-induced fluorescence sensing with the selectivity of capillary electrophoresis. The detection module contains components for dual-optical fibre, on-capillary fluorescence detection. A micellar electrokinetic capillary chromatography mode is utilized to assess the sensor for in situ monitoring of neutral toxins, particularly aflatoxins. Short analysis periods (5–10 min), high separation efficiency, low nanomolar aflatoxins detection limits, and regulated operation resistant to sample matrix effects are some of the salient characteristics (Dickens and Sepaniak 2000a, b).

2. **Enzyme-free catalytic DNA circuit**
A biosensor based on catalytic DNA circuitry has been developed for enhanced AFB1 detection. The colorimetric readout makes use of streptavidin-functionalized gold nanoparticles and biotinylated hairpin DNA probes to enable the detection of AFB1 at concentrations as low as 10 pM with the unaided eye. Robust performance is ensured by the ultrasensitive assay's cascaded signal amplification through toehold-mediated strand displacement events. This easy-to-use sensor has potential for point-of-use AFB1 monitoring in food and environmental sample sets (Chen et al. 2016).

3. **Aptamer based detection**
   To detect AFB1 in food, the study presented an aptamer-based biosensor that uses a layered method using poly (amidoamine) dendrimers on a gold electrode. Using electrochemical impedance spectroscopy and cyclic voltammetry, the biosensor produced repeatable and sensitive results in the AFB1 concentration range of 0.1–10 nM. The efficiency of the sensor was validated in contaminated peanut extract and spiked peanut-corn snacks, demonstrating specificity to AFB1 (Castillo et al. 2015).
4. **Ultra-sensitive magnetic relaxation sensing**
   Zhao et al. (2021) developed an extremely sensitive way to detect the dangerous mycotoxin AFB1, using magnetic relaxation sensing. The sensor showed fast and extremely sensitive detection of AFB1, with a low detection limit of 0.35 pg/mL and a linear range of 10 pg/mL–10 ng/mL. Application to samples of animal feed shown its potential for useful application in real-world situations (Zhao et al. 2021).
5. **Highly Sensitive Molecularly Imprinted Electrochemical Sensor**
   Using gold nanoparticles and electro polymerization, a sensitive electrochemical molecularly imprinted sensor was created for the detection of AFB1. A promising method for sensitive AFB1 detection was made possible by the sensor's dependence on π-π interactions, which enabled specific AFB1 recognition. Using gold nanoparticles and electro polymerization, a sensitive electrochemical molecularly-imprinted sensor was created for the detection of AFB1 (Jiang et al. 2015).
6. **Liquid crystal-based immunosensor**
   Researchers developed a novel liquid crystal (LC) cell system to observe the immune competition reaction between an antibody and aflatoxin. With a low antigen detection limit of 100 pg/mL, the method demonstrated high specificity and provided an easy-to-use, instrument-free method for the detection of aflatoxin visible to the unaided eye (An and Jang 2018).
7. **Amplified π-shape electrochemical aptasensor**
   Accurate AFB1 detection through electrochemical sensing was suggested, employing exonuclease I (Exo I) and an aptamer-complementary strands of aptamer (CSs) complex. On the electrode surface, the complex took the form of a π-shape structure, serving as a double-layer physical barrier for high-sensitivity detection. With recoveries ranging from 95.4 to 108.1%, the aptasensor successfully analysed AFB1 in grape juice and human serum samples that had been tampered with (Abnous et al. 2017).
8. **SPR nanosensor with gold nanoparticles**
   Enhanced surface plasmon resonance (SPR) nanosensors were used to develop a highly sensitive plasmonic sensing method for the detection of AFB1. An SPR gold chip was coated with molecularly imprinted polymers containing gold nanoparticles, producing a low detection limit. The sensor proved to be selective, reusable, and stable in storage by successfully detecting AFB1 in a variety of food samples (Akgönüllü et al. 2020).
9. **SERS aptasensor**
   A surface-enhanced Raman scattering (SERS) sensing approach was created to detect AFB1 with high sensitivity. Using an aptamer that has been partially hybridized with complementary DNA, the strategy enables the release of complementary DNA upon recognition of AFB1. After DNA hybridization was used to capture the SERS tag on a gold surface, it demonstrated excellent AFB1 detection sensitivity and selectivity (Li et al. 2017).

All the emerging sensing and monitoring technologies are briefly explained with their basic principle, advantages, and disadvantages in Table 2.

Future directions and research needs for aflatoxin management

Aflatoxin control efforts are severely hampered by climate change because it modifies the environmental factors that affect fungal growth and toxin production. One effective way to reduce aflatoxin contamination in the face of climate change is to cultivate crops that are climate resilient. Table 3 lists the major emerging sensing and monitoring technologies in use to determine aflatoxin contamination.

1. Studying aflatoxin resistant traits

Because of limited resistant germplasm and complex genetics, developing crop varieties resistant to aflatoxin remains difficult even with preventive measures in place. Aflatoxin contamination has not received as much attention as other crops although quantitative trait locus (QTL) mapping is an invaluable technique for examining complex traits. A high-density linkage map and a resistant Recombinant Inbred Line (RIL) population can be used which can help in finding QTLs for aflatoxin accumulation resistance and/or fungal infection resistance, providing information for accelerated breeding techniques in a variety of crops (Yu et al. 2019).

2. Studying resistance mechanism for aflatoxin

The composition of the seed coat, active oxygen species, membrane lipid peroxidation, phytoalexin accumulation, and the presence of antifungal proteins such lipid transfer protein and trypsin inhibitor are some of the mechanisms of resistance against Aspergillus fungi, which produce aflatoxins. By addressing concerns about

Table 3 Comparing different technologies used for emerging sensing and monitoring technologies to be used for aflatoxin detection in a changing climate

S.no.	Technology	Principle	Advantage	Disadvantage	Reference
1	Modular separation-based fiber-optic sensors	Light propagation through optical fibers	• High sensitivity • Precision • Immunity to electromagnetic interference • Multipurpose sensing	• Expensive • Intricate detecting systems • Need for exact installation processes	Dickens and Sepaniak, (2000a, b); Pendão and Silva (2022)
2	Enzyme-free catalytic DNA circuit	Production a lot of output DNA by using DNA strands as catalysts, which may be utilized repeatedly in the catalytic cycle without being wasted	• Effective catalysis with great selectivity • Modularity for intricate biological processes • Versatile uses across analytical formats • Streamlined design, particularly in catalysed hairpin assembly	• Enzyme-free catalytic DNA circuits can be challenging • Component optimization • Restrictions in certain situations	Jiang et al. (2012); Li et al. (2011); Zhang et al. (2021)
3	Aptamer based detection	Three-dimensional structures—allow for the highly precise and affinity-based detection of target molecules	• Wide range of targets recognized • Easily synthesized and modified • Tailored design that optimizes detection for applications	• Use of complex equipment • Training of staff required • Accuracy of detection may be impacted by external signal interference	Guo et al. (2020); Schüling et al. (2018); Song et al. (2012)
4	Ultra-sensitive magnetic relaxation sensing	Use of magnetic nanoparticles, which can be accurately monitored and have a specific relaxation behavior when subjected to a magnetic field	• Great sensitivity, specificity, and adaptability • Accurately detect analytes at low concentrations	• Expensive • complicated apparatus • temperature and equipment requirement	Bal et al. (2012); Min et al. (2012); Murzin et al. (2020)
5	Highly Sensitive Molecularly Imprinted Electrochemical Sensor (MIECS)	entails the synthesis of a polymer matrix containing particular target molecule recognition sites	• Superior sensitivity, selectivity, and adaptability • Economical detection of a wide range of targets	• Limited stability caused by external influences • Intricate designs • Limited application	Yang et al. (2018a, b); Zhou et al. (2022)
6	Liquid crystal-based immunosensor	Liquid crystal-based immunosensors are biosensors that employ liquid crystals (LCs) as the sensing component to identify certain biomolecules, such as nucleic acids, enzymes, or antigens	• High sensitivity biomolecule detection at low concentrations	• Labor-intensive customization • Lengthy readout periods • Poor sensitivity	Perera et al. (2022); Qu and Li (2022); Rouhbakhsh et al. (2022)
7	Amplified π-shape electrochemical aptasensor	The precise binding of aptamers to their target molecules, resulting in a change in the electrochemical signal	• High sensitivity and selectivity for label-free detection • Precise and economical real-time identification of target compounds	• Complicated design • Complex sample matrices	Abd-Ellatief and Abd-Ellatief, (2021); Wei et al. (2019); Yuan et al. (2023)
8	SPR nano sensor with gold nanoparticles	When target molecules are immobilized on a sensor surface, surface plasmon resonance (SPR) nano sensors SPR phenomenon to increase sensitivity and selectivity for target molecule detection	• Narrow size distribution • Simple synthesis • Effective surface modification for recognition • Increased sensitivity	• Non-specific binding of gold nanoparticles may provide a barrier to detection accuracy • Complicated sample matrices	Arvizo et al. (2010); Guo et al. (2013); Li et al. (2013)

Table 3 (continued)

S.no.	Technology	Principle	Advantage	Disadvantage	Reference
9	SERS aptasensor	Aptamers, which are immobilized on a metal surface such as gold or silver nanoparticles, are used by SERS aptasensor for molecular identification by collecting the vibrational modes of molecules adsorbed on the metal surface	• High sensitivity, selectivity, and multiplex detection • Precise and concurrent identification at low concentration	• Reduced detection accuracy	Wei et al. (2019); Zahra et al. (2021)

food safety, developing crop types that are resistant to fungal infection—like maize in Africa—is made easier with an understanding of these resistance traits (Liang et al. 2009).

3. Exploring potential of RNA interference

Five aflatoxin-synthesis genes were silenced in peanut plants using RNA interference (RNAi), which significantly (up to 100%) reduced the accumulation of AFB1 and AFB2 in comparison to controls. This novel technique uses small RNA sequencing, ultra-performance liquid chromatography (UPLC), and real-time PCR to measure aflatoxin levels while analysing a limited number of seeds. Aflatoxin control in transgenic peanut seeds through RNA interference (RNAi) holds potential for enhancing food safety and agricultural practices worldwide (Arias et al. 2015).

4. Employing integrated approaches

A comprehensive plan has been developed by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and collaborators to reduce *Aspergillus flavus* infestation and subsequent aflatoxin contamination in crops such as groundnuts (peanuts), maize, and sorghum. Host plant resistance, soil amendments, appropriate harvesting techniques, biocontrol agents, and awareness campaigns are all included in this strategy. This economical, scalable method can be suitable for both commercial and subsistence farming and provides a workable solution to aflatoxin-related issues in developing nations (Waliyar et al. 2008).

5. Identification of molecular markers

Given the polygenic nature of *A. flavus* resistance, molecular marker identification is essential for transferring traits into viable genetic backgrounds in peanuts. Effective breeding may be achieved by converting an amplified fragment length polymorphism (AFLP) marker into a Sequence Characterized Amplified Region (SCAR) marker, such as "AFs-412," associated with *A. flavus* resistance. Furthermore, DNA markers linked to decreased aflatoxin accumulation in interspecific hybrids can demonstrate the potential of molecular markers to increase the effectiveness of selection (Bhatnagar-Mathur et al. 2015).

6. Exploring potential of radiations

Gamma (γ) radiation, particularly from a cobalt-60 source, is known to be effective in preserving agricultural and food products by damaging the DNA of microorganisms such as *Aspergillus flavus*. However, different factors like food composition, radiation dose, and fungal strain affect how effective γ-irradiation is. In samples of wheat grains and nuts, UV irradiation—more especially, UV treatment has demonstrated promise in removing aflatoxins (Udomkun et al. 2017).

7. Designing a multi-faceted strategy

Farmers in regions such as Asia and Africa have been reluctant to adopt modern pre-harvest and post-harvest practices because *A. flavus* infection in crops does not immediately affect consumer health or yields. A comprehensive approach involving precise phenotyping, diverse genetic populations, and advanced genetic and genomic tools is necessary to effectively address aflatoxin contamination throughout the food chain. A viable and long-lasting solution to this intricate problem is to leverage genetic resistance and combine it with contemporary genetics and post-harvest management techniques (Pandey et al. 2019).

8. Changing packaging practices

Aflatoxin contamination can result from physicochemical changes and fungal development brought on by storage environment factors like temperature and humidity (Murdock et al. 2012). Aflatoxin contamination in maize and groundnuts is effectively suppressed by using hermetic multi layered bags such as Purdue, even though smallholder farmers in low-income nations frequently employ conventional storage techniques. These bags provide an affordable way to control aflatoxin in grains that are being stored because of their hermetic technology, which lowers moisture absorption and oxygen influx (Williams et al. 2014).

Way forward

Developing crop varieties that are resistant to fungi remains a challenging task, even with the numerous strategies available for mycotoxin control. Biocontrol with atoxigenic strains of *Aspergillus flavus* is currently recommended for pre-harvest management of aflatoxins. However, only atoxigenic strains are used commercially, and post-harvest treatments still pose certain risks. Aflatoxin contamination can be reduced by focusing on the identification of naturally occurring inhibitors and secondary metabolites. Biotechnological techniques, such as tissue culture, genetic transformation, and omics technologies, show promise for boosting crop resistance to *A. flavus*, supporting long-term food security and environmental preservation even as conventional breeding tackles certain issues (Eshelli et al. 2018).

Conclusion

The intricate relationship between aflatoxin risk and climate change is addressed in detail in this comprehensive review, which highlights the pressing need for mitigation. It examines how the environment affects the production of aflatoxin, recognizing the limitations of mechanistic models such as APSIM. The significance of surveillance and awareness is emphasized by the discussion of climate-resistant crops, dynamic risk assessment, advanced detection technologies, and regulatory considerations.

The article's conclusion emphasizes the need for continued research and adaptable tactics while arguing for cooperative efforts to address aflatoxin issues in the context of a changing climate.

Abbreviations

AFB1	Aflatoxin type B1
AFB2	Aflatoxin type B2
AFM1	Aflatoxin type M1
AFG1	Aflatoxin type G1
AFG2	Aflatoxin type G2
HCC	Hepatocellular Carcinoma
EU	European Union
US	United States
EFSA	European Food Safety Authority
µg/kg	Microgram per kilogram
RH	Relative Humidity
CO_2	Carbon Dioxide
FFA	Free Fatty Acids
wa	Water Activity
APSIM	Agricultural Production Systems Simulator
SSA	Sub-Saharan Africa
CAC	Codex Alimentarius Commission
FAO	Food and Agriculture Organization
WHO	World Health Organization
MPLs	Maximum Permitted Levels
FDA	Food and Drug Authority
HBV	Hepatitis B Virus
IPM	Integrated Pest Management
LC	Liquid Crystal
pg/ml	Picogram per microliter
Exo I	Exonuclease I
CSs	Complementary Strands
SPR	Surface Plasmon Resonance
SERS	Surface-Enhanced Raman Scattering
DNA	Deoxyribo Nucleic Acid
MIECS	Molecularly Imprinted Electrochemical Sensor
nM	Nano Molar
ng/mL	Nanogram/microlitre
QTL	Quantitative Trait Locus
RIL	Recombinant Inbred Line
RNA	Ribo-Nucleic Acid
UPLC	Ultra-performance liquid chromatography
PCR	Polymerase Chain Reaction
RNAi	RNA interference
ICRISTAT	International Crops Research Institute for the Semi-Arid Tropics
AFLP	Amplified fragment length polymorphism
SCAR	Sequence Characterized Amplified Region
γ	Gamma
UV	Ultra Violet
PICS	Purdue Improved Crop Storage

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