Climate Change and the Emerging Risk of Mycotoxin Contamination: A Food Safety Perspective

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Abstract
Climate change is a major factor influencing agricultural production and global food security, causing significant changes in the ecology of toxigenic fungi and the profile of food contaminants. Rising average temperatures, humidity fluctuations, and the increased frequency of extreme weather events contribute to intensified abiotic stress on crops and promote conditions favorable to fungal mycotoxin biosynthesis, particularly in corn and wheat. Recent studies highlight a geographical expansion of the risk of mycotoxin contamination in regions previously considered safe, such as Southern and Eastern Europe. Aflatoxins produced by *Aspergillus flavus* are increasingly reported in areas affected by prolonged drought and high temperatures, whereas *Fusarium spp*. thrive in humid regions, producing toxins such as deoxynivalenol and zearalenone. These changes threaten not only crop quality but also public health, with potential implications for the incidence of chronic diseases linked to prolonged exposure to food contaminants. To enhance agricultural resilience and ensure consumer protection, it is essential to implement integrated strategies, including applied climate monitoring, the use of resistant crop varieties, improved harvesting and storage practices, and stricter regulations regarding mycotoxin control. This paper aims to analyze the interaction between climate variability and mycotoxin occurrence, with a focus on the implications for food safety and the identification of future research directions in the context of climate change.

Keywords: abiotic stress, agricultural resilience, climate change, food safety, mycotoxins, toxigenic fungi.

Introduction

Climate change is having an increasingly significant impact on global food safety. Rising temperatures, changes in precipitation patterns, and the intensification of extreme weather events are disrupting the balance of agricultural ecosystems and the interactions between crops and fungal pathogens [1]. Mycotoxins - toxic compounds produced by phytopathogenic fungi such as *Aspergillus, Fusarium*, and *Penicillium,* have long posed a major challenge to food safety, frequently contaminating harvests [2]. According to recent studies, climate change may worsen this issue by expanding high-risk areas and increasing contamination levels in already affected regions [3]. Climate plays a important role in the development of toxigenic fungi and mycotoxin production, both during crop growth and post-harvest [1]. Climate change-especially higher temperatures and humidity fluctuations can shift the geographic distribution of crops and pathogens, promoting the emergence of new pathosystems [4]. One example is the increased incidence of aflatoxins in northern Italy and Eastern Europe, associated with regional warming in recent years [5]. Mycotoxins remain a global threat, affecting staple crops such as maize, wheat, peanuts, and coffee. Without effective control, contaminated food may enter the food chain,

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exposing populations to toxic effects [6]. Even in regions with strict regulations, contamination persists: between 2010 and 2019, a pan-European study revealed frequent presence of deoxynivalenol in cereals, while aflatoxins and ochratoxin A were predominantly found in southern Europe [7]. Awareness of the risks associated with mycotoxin contamination in the context of climate change has grown significantly in the past decade. The scientific community and regulatory authorities warn that global warming may exacerbate existing food safety issues [8]. This article analyzes how climatic factors influence the emergence of mycotoxins, the shifting geographic distribution of risk, the implications for public health, and the necessary adaptation strategies. The analysis draws on recent scientific literature, offering an up-to-date perspective on a pressing issue.

Climatic Factors Influencing Mycotoxin Production

The production of mycotoxins by toxigenic fungi is strongly influenced by climatic conditions, particularly temperature and humidity. These variables affect both fungal development and their ability to synthesize toxic metabolites [9]. Each fungal species has an optimal environmental range, and deviations from these conditions may stimulate or inhibit mycotoxin production. *Fusarium spp.*, responsible for deoxynivalenol (DON) and zearalenone (ZEA), thrive in cool and humid climates, while *Aspergillus flavus*, the producer of aflatoxin B_1, prefers hot and dry environments [10]. A 17-year study conducted across 12 countries revealed that levels of aflatoxins and fumonisins increase proportionally with temperature, whereas DON and ZEA levels tend to decrease under the same conditions. These findings support the idea that global warming favors thermophilic fungi with higher toxic potential [11]. Humidity plays a critical role in substrate colonization and mycotoxin synthesis. Heavy rainfall, particularly during sensitive crop growth stages (e.g., cereal flowering), creates favorable conditions for *Fusarium* infection. Furthermore, alternating periods of drought and moisture increase the risk of contamination, as water stress weakens plants and facilitates fungal colonization. Documented cases of acute aflatoxicosis, such as the 2004 outbreak in Kenya, confirm these relationships [12]. The dew point, as a combined indicator of temperature and humidity, has proven useful in predictive models: high values favor *Aspergillus* development and aflatoxin production. In contrast, *Fusarium* thrives under excessively humid and moderately warm conditions, commonly seen during rainy summers [10, 13]. An increasingly discussed climatic factor is atmospheric carbon dioxide (CO_2), whose projected rise may indirectly affect plant-pathogen interactions and substrate composition. Experimental studies have explored the combined effects of temperature, humidity, and CO_2 on toxigenic fungi, suggesting that these conditions may enhance the expression of genes involved in toxin biosynthesis [14]. In *Aspergillus flavus*, it has been observed that high temperatures combined with elevated CO_2 levels can intensify aflatoxin production. These findings highlight the important role of complex interactions between climatic factors in shaping the risks associated with mycotoxin contamination [15].

Extreme weather events, such as heatwaves, droughts, and torrential rains, create favorable conditions for contamination. For instance, drought followed by rain can cause cracking in plant tissues, exposing them to fungal infection. Once infected, humid conditions can rapidly trigger mycotoxin synthesis, even before harvest or during storage [16].

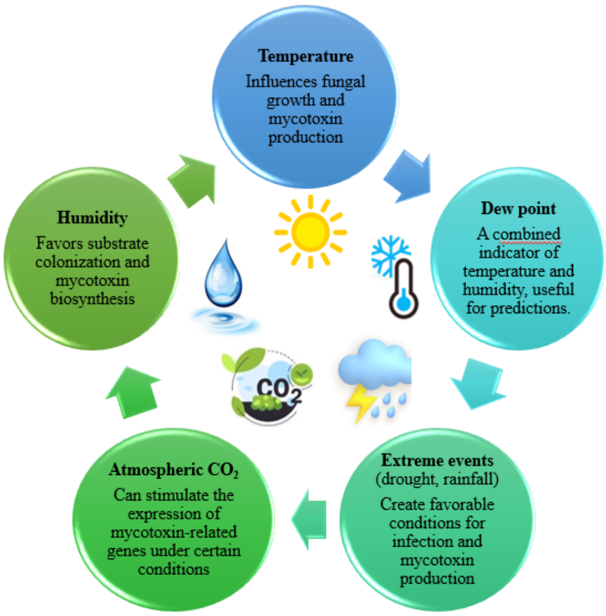

Figure 1. Essential climatic factors in mycotoxin synthesis

The role of climate-mediated biological interactions is particularly important in the ecology of toxigenic fungi. Higher temperatures may favor the proliferation of insect pests, which act as vectors for fungal spores or cause plant injuries that facilitate colonization. Thus, heat, drought, and pests interact synergistically, amplifying the risk of mycotoxin contamination, while cooler, wetter conditions favor other species, such as *Fusarium* [17]. Climate change promotes thermophilic fungi and alters the type and levels of mycotoxins in the food chain. Understanding the interactions between climatic factors and the ecology of toxigenic fungi is essential for risk prevention and the adaptation of agricultural strategies [18].

Geographical Shifts in Contamination Risk

As the climate changes, the risks associated with mycotoxins are being redistributed geographically. Regions previously unaffected are becoming vulnerable, and the spectrum of dominant contaminants is shifting. A major contributing factor is the displacement of agro-climatic zones, which leads to the relocation of crops and, consequently, of pathogenic agents [19]. A relevant example is Europe: the southern part of the continent (Italy, Spain, the Balkans) has historically been exposed to aflatoxin contamination, while the north has been dominated by toxins produced by *Fusarium*. However, global warming is pushing maize cultivation further north, increasing the risk of fungi such as *Aspergillus flavus* appearing in areas where they were previously absent [16]. Climate models suggest that a +2°C increase could allow maize cultivation to expand into Central and Northern Europe, while reducing optimal growing areas in the south. This migration carries the risk that hybrids may encounter pathogens for which they have no developed resistance [20]. At the same time, toxigenic fungi are expanding their range. Aflatoxin B_1 contamination events have already been reported in Italy, Serbia, and Croatia during drought years, sometimes exceeding permissible limits. The risk may also increase in other countries like Romania or Hungary, where the climate is becoming more favorable to *A. flavus* development [1]. According to Paterson and Lima, global warming of 2-5°C could turn aflatoxins into a major food safety risk even in countries where they were not previously a significant concern, such as Hungary or Ukraine, due to shifts in fungal distribution and replacement of dominant species [21]. In vineyards in southern Spain, decreasing humidity has favored *Aspergillus niger*, leading to contamination with fumonisin B_2 instead of OTA, an unexpected and unregulated contaminant in wine. In Italy, hotter summers have allowed *A.* flavus to replace *Fusarium verticillioides* in maize, increasing toxicological risk [6]. Globally, tropical and subtropical regions may also experience internal redistributions. In Malawi, for example, it is estimated that northern areas, previously relatively safe, could record dangerous levels of aflatoxin B_1 in the coming decades. This type of risk directly impacts food security in developing countries, where diets rely heavily on local production [22]. In Asia, rising temperatures and prolonged drought may extend the risk period for maize and peanuts, while contamination is increasingly reported in unusual products such as dried fruits and spices [3, 23]. In the U.S., southern states report higher aflatoxin levels in maize and peanuts during drought years, while in California, climate change has increased aflatoxin contamination in pistachio and almond orchards [24]. Another essential aspect is the extension of the growing season in extreme northern or southern regions, which allows for the cultivation of new species and prolongs the activity of pathogenic fungi. Moreover, changes in plant phenology (e.g., earlier flowering or maturation) may create "windows of vulnerability," exposing crops to infection during critical periods [6]. Under the influence of climate change, the geographical distribution of mycotoxin contamination risk is shifting significantly. Temperate zones previously considered stable are now reporting sporadic aflatoxin contamination events, while traditionally affected regions are experiencing changes in the mycotoxin profile, such as the increasing prevalence of *Fusarium graminearum* (a producer of deoxynivalenol, DON) in Central and Northern Europe, replacing less toxigenic species [8]. This evolution calls for a proactive approach: expanding monitoring systems, including in previously unaffected regions, and adopting appropriate control measures. In a global context, international cooperation becomes essential, given the mobility of pathogens and the transnational nature of climate change [25].

Implications for Public Health and Food Safety

Mycotoxins, toxic metabolites produced by various fungal species (such as *Aspergillus, Fusarium*, and *Penicillium*), pose a major risk to human health, food availability, and the agricultural economy. Their toxic effects range from acute intoxications (which can cause severe symptoms or even death) to chronic conditions such as cancer, growth disorders, immunosuppression, or endocrine dysfunction [26]. Among the most dangerous, aflatoxins, particularly B_1, have been classified by the International Agency for Research on Cancer (IARC) as Group 1 carcinogens, associated with a higher incidence of hepatocellular carcinoma, especially in individuals infected with the hepatitis B virus [27]. At high doses, they can cause acute toxic hepatitis, while chronic exposure contributes to developmental delays and immunosuppression in children. Deoxynivalenol (DON), produced by *Fusarium*, causes nausea, vomiting, and anorexia upon acute exposure, while long-term exposure may lead to intestinal inflammation and malabsorption disorders [28]. Other notable mycotoxins include ochratoxin A (nephrotoxic and possibly carcinogenic), zearalenone (with estrogenic effects), fumonisins (linked to esophageal cancer and neural tube defects), patulin (toxic to the gastrointestinal tract), and Claviceps alkaloids (which can cause ergotism with severe vascular and neurological symptoms) [29]. Biomonitoring studies (e.g., HBM4EU) already indicate exposure levels above safe limits for DON in approximately 14% of the adult population in Europe, a percentage likely to increase due to climate change [30]. The most vulnerable groups are children, pregnant women, infants, and agricultural workers. Prenatal exposure, for instance to fumonisins, is associated with a higher risk of congenital malformations, and young children, due to their higher food intake relative to body weight, can accumulate dangerous doses. Inhalation of contaminated dust particles in agricultural settings can also represent an additional exposure route [31]. In tropical and subtropical regions, where temperatures are rising and drought periods are becoming more frequent, food contamination with mycotoxins may intensify, increasing the burden of associated diseases. For example, a severe aflatoxin poisoning outbreak in Kenya (2004) led to 125 deaths, triggered by drought and improper maize storage [8, 23]. Beyond health effects, mycotoxins also cause considerable economic losses. Contaminated crops must be destroyed or sorted, reducing food availability and affecting farmers' income. Global estimates suggest hundreds of millions of dollars are lost annually due to mycotoxin contamination, with costs likely to rise as climate crises worsen [2]. Developing countries are the most affected, losing both domestic food supplies and export revenues (for example, Africa frequently loses peanut and maize shipments rejected on international markets due to aflatoxins) [32]. Even in developed countries, contamination impacts both food and feed chains. Contaminated grains require additional imports, and toxic feed reduces livestock productivity and may lead to dangerous residues, such as aflatoxin M_1 in milk [6, 33]. In dry years, Europe has reported exceedances of aflatoxin M_1 limits in dairy products, reflecting the direct connection between feed safety and food safety [34]. This interconnection is addressed through the "One Health" approach, which emphasizes the relationship between human, animal, and environmental health. In the context of the climate crisis, it is essential to strengthen contamination monitoring systems, update toxicological regulations (including those for emerging mycotoxins), and implement public education campaigns [35]. Protecting vulnerable groups, along with investing in research and food safety infrastructure, becomes a top priority to mitigate the growing impact of this accelerating risk [36].

Managing Mycotoxin Risk in the Context of Climate Change

Climate change increases the risk of mycotoxin contamination throughout the food chain, requiring an integrated approach that includes interventions at every stage, from cultivation, harvesting, and storage to processing and regulation. Effective risk mitigation demands cooperation across agronomy, plant pathology, food science, and climate forecasting [8].

Adaptive Agricultural Practices and Genetic Improvement

Preventing fungal infection in the field is essential to limiting contamination. Under warmer and drier climate conditions, adopting resilient agricultural practices becomes vital: cultivating varieties/hybrids resistant to abiotic stress (heat, drought) and toxigenic fungi such as *Fusarium* (DON) or *Aspergillus* (aflatoxin). Breeding programs aim to integrate resistance genes into major crops (maize, wheat, peanuts) [37]. There are already maize hybrids resistant to *A. flavus* or drought, which produce significantly lower levels of aflatoxins under water stress conditions [6]. Other important practices include crop rotation (to prevent pathogen buildup in the soil), tillage that eliminates sources of inoculum (e.g., infected crop residues), adjusting sowing dates (to avoid sensitive plant phases during extreme heat), and strategic irrigation. Integrated pest management (targeting insects and rodents) is also critical, as these pests facilitate fungal entry and spread in plants [38].

Biocontrol and Plant Protection Treatments

Increasingly strict restrictions on chemical fungicides in the EU (with about 50% of active substances being withdrawn) encourage the adoption of alternative solutions such as biological control agents. These act through competition or antagonism against toxigenic fungi. A successful example is AflaSafe, a product containing atoxigenic strains of *A. flavus*, used to reduce aflatoxin contamination in maize and peanuts. By preferentially colonizing the crop, these strains prevent the establishment of toxigenic variants, reducing contamination by as much as 80-90% [39]. Other beneficial microorganisms, such as species of *Trichoderma or Bacillus*, are also being studied for their ability to inhibit *Fusarium* development on cereals. However, the efficacy of biological agents can be affected by extreme conditions, many strains do not survive well under drought or high temperatures. Therefore, selecting strains resistant to climate stress, including elevated CO_2 levels, is necessary [40]. Conventional fungicides (triazoles, strobilurins) remain useful, especially for treating cereal heads, but their effectiveness can be compromised by rain, heat waves, and fungal resistance, which justifies the broader integration of methods under Integrated Pest Management (IPM) [41].

Harvesting and Storage Management

Contamination can continue or even begin post-harvest, especially if drying is delayed due to high temperatures or elevated humidity. Maize, for example, must be dried quickly to below 13-14% moisture to prevent the growth of fungi such as *Aspergillus* or *Penicillium*. Investments in drying and controlled storage infrastructure (ventilation, airtight silos, hermetic bags) are becoming increasingly important [42]. Monitoring storage conditions is essential: temperature, humidity, CO_2 sensors, or even "electronic noses" can detect hotspots where molds may begin to develop. IoT technologies allow for rapid interventions to prevent the spread of contamination [43]. Decontaminating contaminated grains is challenging because many mycotoxins are thermally stable. However, certain methods, optical sorting, treatments with adsorbents (clays, activated charcoal), or detoxifying enzymes, can significantly reduce the risk, especially in animal feed. Physical methods such as ozonation, irradiation, or cold plasma treatments are under development but require careful regulation to ensure food safety [44].

Predictive Monitoring and Early Warning Systems

Integrating climatic and epidemiological data allows for anticipating contamination risks. Mathematical models such as AFLA-maize (for aflatoxin in maize) or those for *Fusarium* (DON in wheat) are already used in Europe, estimating risk based on daily weather data [6]. These models indicate a significant increase in contamination under warming scenarios; for example, a +2°C rise could increase aflatoxin levels in southern Europe and DON levels in the north, where *Fusarium graminearum* will benefit from a warmer and wetter climate [45]. However, many models do not include important factors such as insect infestations or do not provide direct adaptation solutions. Work is ongoing to develop integrated models that incorporate variables like planting date, cultivar type, or land use scenarios to support adaptive agricultural policies [46]. In practice, some countries (e.g., Italy, Serbia) are testing SMS alert systems that notify farmers when the risk of aflatoxin increases, recommending early harvesting or preventive measures. The future of these systems involves using artificial intelligence and local sensors to issue personalized warnings weeks before the risk arises [47].

Public Policy and the One Health Approach

Managing mycotoxin risk requires political support and regulations adapted to new climate realities. Authorities need to update legal limits for emerging mycotoxins (e.g., aflatoxins in maize in northern regions or DON-derived compounds). It is also necessary to expand monitoring through national surveys that include less well-known toxins [48]. European strategies (e.g., "Farm to

Fork," EFSA) recognize climate change as a major source of emerging risks to food safety. In this context, the One Health approach, which integrates human, animal, and environmental health, becomes essential. Collaboration is needed among ministries of agriculture (for field control), health (for food and animal product safety), and environment (for adaptation planning) [49]. At the same time, research and innovation are fundamental pillars: developing portable sensors, biosensors, molecular studies on toxin biosynthesis, as well as economic evaluations of adaptation measures can guide strategic decisions. International collaboration plays a key role, Europe can learn from African experiences in biocontrol, while African countries can benefit from the EU's expertise in regulation and monitoring [50].

Conclusions

Climate change profoundly affects health and food safety, with one of the less visible but critical impacts being the increased risk of mycotoxin contamination. Changes in temperature, humidity, and the frequency of extreme weather events directly influence the production and distribution of these fungi-produced toxins, creating new risk zones and intensifying contamination in already affected areas. This phenomenon threatens the food chain and public health by increasing the incidence of serious diseases. To address this challenge, it is necessary to deepen our understanding of the interactions between climatic factors and fungi, including long-term studies and predictive models to help farmers manage risks effectively.Innovative rapid detection technologies and new detoxification methods can mitigate the impact of mycotoxins. Furthermore, integrating these aspects into national policies and fostering international cooperation are vital to prevent food crises. Overall, an interdisciplinary and coordinated approach, grounded in science and awareness, is essential to protect public health and ensure food safety amid climate change.

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