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Climate-based Aflatoxin Risk Assessment in Maize using a Temperature-derived Index: Evidence from Albania

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ABSTRACT

Background: This study evaluates the impact of climate variability on the risk of aflatoxin contamination in maize across Albania's major agricultural regions over the period 2004-2024. Rising temperatures and more frequent droughts, driven by climate change, are identified as major factors promoting the growth of *Aspergillus flavus* and the production of aflatoxins, posing a threat to food and feed safety.

Methods: A temperature-based aflatoxin risk index (ARI) was developed, defined as the proportion of days during the maize growing season (May-September) with maximum temperatures exceeding 33°C. Spatial and temporal patterns were assessed across six main producing regions: Fier-Lushnjë, Durrës, Elbasan, Shkodër, Gjirokastër and Korçë.

Result: The findings indicate a clear upward trend in high-risk conditions, particularly in western lowland regions, where ARI values frequently exceeded 60%, indicating high to very high risk. In contrast, the inland region of Korçë exhibited consistently lower ARI values due to cooler climatic conditions. Seasonal analysis revealed that July-August represents the critical risk window. These findings align with broader climate-driven trends observed in Southern Europe and highlight the increasing vulnerability of Albania's maize production systems to mycotoxin contamination. While the ARI serves as a simple and scalable screening tool, integrating additional environmental variables is recommended to improve predictive accuracy.

Key words: Aflatoxins, *Aspergillus flavus*, Climate variability, Maize, Risk assessment/aflatoxin risk index.

INTRODUCTION

Food safety remains a critical global challenge, with contaminated food contributing substantially to disease burden and economic losses worldwide (Altomare *et al*., 2021; Wu *et al*., 2014). According to the world health organization (WHO), it is estimated that 600 million, nearly one in 12 people worldwide, are exposed to contaminated food and suffer from foodborne illnesses annually, underscoring the importance of identifying and mitigating risks across the food supply chain, with approximately 420,000 deaths each year (WHO, 2024).

Among food contaminants, natural toxins-particularly mycotoxins-pose a significant and persistent threat to human health and animal production systems. Mycotoxins are estimated to contaminate a substantial share of global food crops, with some estimates suggesting that up to 25% of the world's crops may be affected (Eskola *et al*., 2019; Topi *et al*., 2021). These toxic secondary metabolites are produced by filamentous fungi, commonly in the genera Aspergillus, Fusarium and Penicillium. Among these, aflatoxins are considered the most hazardous due to their potent carcinogenic, hepatotoxic and immunosuppressive effects. Aflatoxin B1 (AFB1), in particular, has been classified as a Group 1 carcinogen by the International agency for research on cancer, with strong epidemiological evidence linking exposure to hepatocellular carcinoma. These toxins frequently contaminate staple crops such as maize (*Zea mays* L.), posing serious risks to food security, public health and international trade (Munkvold *et al*., 2019).

Aflatoxin contamination is strongly influenced by environmental conditions, particularly temperature and moisture. Optimal growth of *A. flavus*, the primary aflatoxin-producing species, occurs under warm and moderately humid conditions, while toxin production is significantly enhanced at temperatures above 33°C. Consequently, climate change-characterized by rising temperatures, altered precipitation patterns and increased frequency of extreme weather events-has emerged as a key driver of aflatoxin risk worldwide (Cotty and Jaime-Garcia, 2007; Medina *et al*., 2014).

In Southern Europe, including the Balkan Peninsula, recent decades have seen accelerated warming trends that outpace global averages, linked to notable aflatoxin contamination events in maize during extreme heat and drought years such as 2003, 2012 and 2015. Countries such

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as Croatia, Serbia, Romania and Albania have experienced significant outbreaks, underscoring vulnerability to climate-driven mycotoxin risks (Kos *et al*., 2018; Topi *et al*., 2023; Topi *et al*., 2024). Studies highlight the role of climate change in spreading aflatoxin B1-producing molds from tropical regions to the Mediterranean and Central Europe (Baranyi *et al*., 2015; Battilani *et al*., 2016). Data from Albania, including high AFB1 levels in corn (0.32-3550 μg/kg in 2014-2015) and recent research showing mycotoxigenic fungi and AFB1 in corn and wheat (Mato *et al*., 2024a), reveal increasing mycotoxin risks. Albanian cereal surveys also document *Fusarium mycotoxins*, minor unregulated *Aspergillus* and *Penicillium* toxins and wheat quality issues related to food safety, emphasizing the diverse and growing mycotoxin challenges in Albanian agriculture (Topi *et al*., 2021; Topi *et al*., 2024).

Climate change will affect animal production and, consequently, global food security (Kuraz *et al*., 2021; Manjeet *et al*., 2023). Mycotoxin-producing fungi are common components of the epiphytic and endophytic microflora of crops, resulting in natural contamination of crops in the field and during storage (Chukwudi *et al*., 2021). The most hazardous mycotoxins in human foods and animal feeds include aflatoxins, ochratoxins, fumonisins, deoxynivalenol and zearalenone, which pose a serious health hazard (EFSA, 2020). Mycotoxins enter the food chain through preharvest and postharvest fungal infections. Among these, aflatoxin B (AFB1) is the most toxic and is classified as a carcinogen (Mitchell *et al*., 2016)-epidemiological data link AFB1 to liver cancer in humans (Liu and Wu, 2010). Food laws establish maximum allowable levels of contaminants, including aflatoxins (Regulation (EU) 2023/915 on certain contaminants in food. The development of aflatoxigenic molds and the production of AF depend on the type of substrate or crop where they grow (Abrar *et al*., 2013). AFB1 ingested by dairy animals is metabolized and excreted in milk as aflatoxin M1 (AFM1) (Min *et al*., 2021), extending the food safety concern to dairy products. In Albania, AFM1 contamination in milk has also been reported (Tahiri *et al*., 2025), highlighting the downstream impact of field contamination on the broader food chain. Climatic conditions, humidity, temperature, agricultural practices, insect damage and storage conditions vary across different crops, affecting contamination levels (Valencia-Quintana *et al*., 2020).

Aflatoxin risk analysis

The aflatoxin risk index (ARI, %) is not a standardized global metric but rather a calculated value used in specific studies or models to estimate the likelihood of aflatoxin contamination in crops or food products (Chauhan *et al*., 2015). The ARI is a predictive measure used in agricultural and food safety research to estimate the probability or severity of aflatoxin contamination.

ARI is typically derived from models that integrate:

• Weather data (temperature, humidity, rainfall).
• Crop susceptibility (*e.g*., maize, peanuts).
• Fungal growth conditions (*A. flavus* and *A. parasiticus*).
• Historical contamination data.

Monitoring ARI helps mitigate contamination in food supply chains and protect consumer health. Pre-harvest modeling and mitigation of aflatoxins in maize under changing climatic conditions have been extensively reviewed (Dövényi-Nagy *et al*., 2020) providing a scientific basis for climate-sensitive risk indices.

Country production comprises a wide range of crops, including small grains intended for human and feed as well as maize (Mato *et al*., 2024b). Despite increasing awareness at the European level, localized assessments of aflatoxin risk remain limited in Albania. Existing studies indicate a growing prevalence of mycotoxin contamination in maize and other cereals, yet there is a lack of predictive tools tailored to the country's specific climatic and agricultural conditions. This gap hinders the development of effective monitoring and mitigation strategies, particularly in regions where traditional farming and storage practices may exacerbate contamination risks.

This study develops a simplified, temperature-based aflatoxin risk index (ARI) for Albania's major maize regions from 2004 to 2024. It focuses on temperature thresholds linked to aflatoxin production to (i) measure variability in risk, (ii) identify high-risk areas and (iii) offer a practical early assessment tool amid climate change. The results aim to enhance food safety and inform adaptation strategies.

MATERIALS AND METHODS

Study area

The study was conducted across major maize-producing regions of Albania Fier-Lushnjë, Durrës, Elbasan, Shkodër, Korçë and Gjirokastër-which are characterized by mediterranean influences and hot, dry summers (Fig 1). In contrast, the Korçë region has a temperate continental climate. The maize crop is typically cultivated from May to October. These regions were selected for their agricultural importance and varying vulnerability to heat stress and drought. The research project was developed within the research group on food toxins in the Department of Chemistry, Faculty of Natural Sciences, University of Tirana, during the period 2023-2025.

Data collection

Daily maximum air temperature data (T_{max}, °C) for the period 2004-2024 were obtained from regional meteorological monitoring systems. The analysis focused on the maize growing season, defined as May through September, corresponding to key phenological stages: vegetative growth (May-June), flowering (July), grain filling (August) and maturation (September). For each region and year, the number of days with maximum temperature exceeding 33°C was extracted, as this threshold is associated with enhanced aflatoxin production by *A. flavus* (Medina *et al*., 2014; Cotty and Jaime-Garcia, 2007).

Aflatoxin risk index

To quantify the climatic suitability for aflatoxin contamination, a temperature-based Aflatoxin Risk Index (ARI) has been developed (Medina *et al*., 2014). The ARI is defined as:

$$ARI = \frac{N_{Tmax}>33°C}{N_{total}} \times 100$$

Where,

N_{Tmax}>33°C= Number of days during the growing season with T_{max} above 33°C.

N_{total}= Total number of days in the growing season (May-September).

The threshold of 33°C was selected based on experimental and modeling studies indicating optimal conditions for aflatoxin biosynthesis, even though fungal growth may occur at slightly lower temperatures (Medina *et al*., 2014; Cotty and Jaime-Garcia, 2007).

To facilitate interpretation, ARI values were categorized into six risk levels (Table 1).

Trend and spatial analysis

Temporal trends in ARI values were evaluated over the 20-year study period (2004-2024) to identify changes in climatic risk patterns. Regional comparisons were performed to assess spatial variability in aflatoxin risk across different agro-climatic zones.

Descriptive statistics, including mean ARI values and interannual variability, were used to summarize regional differences. The analysis aimed to identify high-risk regions and assess whether the frequency of critical temperature conditions has increased over time.

Assumptions and limitations

The proposed ARI model is based solely on temperature as the primary driver of aflatoxin risk. While temperature is a key factor influencing *A. flavus* growth and toxin production, other environmental variables-such as relative humidity,

Fig 1: Main regions of intensive maize production in Albania.

rainfall, soil moisture and postharvest storage conditions-also play a significant role.

Due to data limitations, these factors were not included in the present model. Therefore, the ARI should be interpreted as a proxy indicator of climatic suitability rather than a direct measure of contamination. Future studies should integrate multi-factorial datasets and validated predictive models to improve accuracy and reliability.

RESULTS AND DISCUSSION

Temporal trends in aflatoxin risk index

Analysis of ARI data from 2004 to 2024 shows a clear increase in high-temperature conditions conducive to aflatoxin production in Albania’s main maize-growing areas. The percentage of days with maximum temperatures above 33°C during the growing season varied significantly from year to year, with a recent increasing trend. Periods of extreme summer heat led to higher ARI values, indicating a greater likelihood of favorable conditions for *A. flavus* growth and aflatoxin formation. Throughout several years of the study, ARI values in lowland regions exceeded the 60% threshold, indicating high to very high risk (Fig 2).

Significant spatial differences in ARI values were observed among the studied regions. Western lowland regions, including Fire-Lushnjë, Durrës and Elbasan, consistently exhibited the highest ARI values throughout the study period. These regions frequently fell within the “high” (41-60%) and “elevated” (61-80%) risk categories, reflecting persistent exposure to temperature conditions conducive to aflatoxin production.

Similarly, Shkodër region showed elevated ARI values, particularly in the summer months, likely due to the combined effects of high temperatures and coastal humidity. Gjirokastër recorded moderate to high ARI levels, with seasonal peaks in July and August, periods of intensified heat. In contrast, the inland region of Korçë consistently had lower ARI values, generally within the “low” to “moderate” risk categories (below 40%). This pattern reflects the moderating effect of higher altitude and temperate continental climatic conditions, which limit the number of days exceeding the critical temperature threshold.

Seasonal distribution of risk contamination

The distribution of high-risk days within the maize growing season was not uniform. The highest frequency of temperatures exceeding 33°C occurred during the mid-to-late summer months, particularly in July and August, corresponding to the silking/flowering and grain-filling stages of maize development. These stages are known to be particularly sensitive to fungal infection and toxin accumulation.

Table 1: Aflatoxin risk classification (ARI) (%), risk level and description.

ARI range (%)	Risk level	Description
0-10%	Very low	Conditions are safe, with minimal risk of aflatoxin contamination.
11-25%	Low	Limited risk, basic monitoring is sufficient.
26-40%	Moderate	Moderate risk, preventive measures and regular checks are recommended.
41-60%	High	Significant risk, strong control measures and testing are advised.
61-80%	Elevated	A major risk, urgent intervention and lab testing are necessary.
81-100%	Critical	Substantial risk, use of crops should be restricted pending thorough analysis.

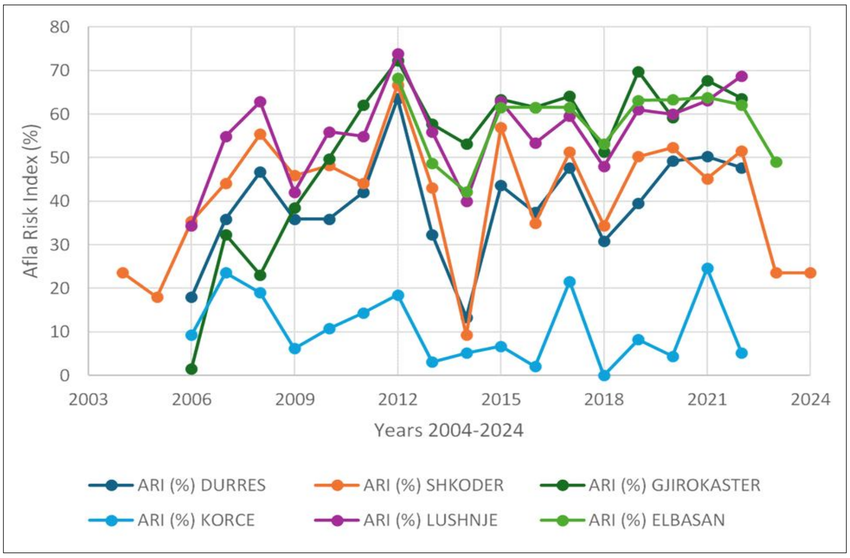

Fig 2: Temporal variation of the aflatoxin risk index across major maize-growing regions.

In early (May-June) and late (September) stages of the growing season, ARI values were substantially lower across all regions, indicating reduced climatic suitability for aflatoxin production. This seasonal pattern highlights the critical importance of mid-summer climatic conditions in determining overall contamination risk.

Regional risk classification

Based on ARI classification thresholds, the analyzed regions can be grouped into distinct risk categories. Durrës and Elbasan regions emerge as high-risk zones, with frequent classification in the "high" to "very high" categories. Shkodër and Gjirokastër can be considered moderate-to-high risk regions, exhibiting substantial interannual variability.

In contrast, the Korçë region represents a comparatively low-risk area, with ARI values rarely exceeding moderate levels. These distinctions reflect underlying climatic gradients and provide a basis for region-specific risk management strategies. These findings are in accordance with previous studies on aflatoxin occurrence in grain and maize from these regions (Topi *et al*., 2023; Mato *et al*., 2024a).

This study presents the first comprehensive climate-based assessment of aflatoxin risk in maize across Albania's major agricultural regions over the last two decades, 2004-2024, beginning with the first reported incidence of maize contamination in Europe (Table 2). Contamination levels are influenced by plant and fungal genetics, management practices and prevailing climatic conditions (Chukwudi *et al*., 2021). The findings show a significant increase in high-temperature conditions conducive to *A. flavus* proliferation and aflatoxin biosynthesis, with pronounced spatial variability across western lowland and inland regions. These results align with and extend the growing body of evidence from neighboring Balkan countries and Southern Europe on the role of climate change in elevating mycotoxin contamination risks.

The elevated ARI values (>60%) in western lowland regions (Fier-Lushnjë, Durrës, Elbasan) align closely with climate warming patterns documented across the Balkan Peninsula and Southern Europe (Baranyi *et al*., 2015; Kos *et al*., 2018). Battilani *et al.* (2016) demonstrated that aflatoxin B1 contamination in maize is increasing across Europe due to climate change, with particular vulnerability in transitional zones such as Southern Europe and the Balkans. Our data support this trend, showing that Albania's western regions, characterized by Mediterranean climates with hot, dry summers, are experiencing intensified heat stress during critical maize phenological stages. This pattern reflects the strong influence of regional climatic conditions on *A. flavus* proliferation and the associated risk of aflatoxin contamination.

The inland region of Korçë, with consistently lower ARI values (<25%, predominantly 'low' risk), represents a climate refuge due to higher altitude and temperate continental conditions. This spatial differentiation mirrors patterns observed in other temperate regions of Europe, where elevation-driven temperature gradients create microclimates less favorable for aflatoxin production. Such regional heterogeneity underscores the importance of localized risk assessments, as emphasized by Medina *et al*. (2014), who demonstrated that even small temperature increases of 2-3°C in transitional zones can substantially elevate aflatoxin risk.

ARI trends align with broader climate change in Southern Europe, where warming exceeds the global average, leading to increased aflatoxin contamination, especially during heat and drought events in Serbia and Romania (Battilani *et al*., 2016; Kos *et al*., 2018). These patterns support the idea that climate change is expanding aflatoxin risks across Europe, notably in transitional zones such as the western Balkans, where small increases in temperature can boost aflatoxin production.

The results reveal increasing vulnerabilities in Albania's maize systems, with frequent ARI values exceeding 60% in western regions, indicating a high aflatoxin risk. Elevated temperatures boost fungal infections and poor drying and storage worsen contamination. The proposed ARI model provides a simplified and practical tool for assessing climatic suitability for aflatoxin contamination, particularly in data-limited environments. Its reliance on temperature thresholds enables straightforward implementation with readily available meteorological data, making it suitable for preliminary risk screening and early warning systems. However, this simplicity also represents a key limitation. Multiple interacting factors, including relative humidity, rainfall patterns, soil moisture, insect damage and storage conditions, influence aflatoxin production. By focusing exclusively on temperature, the ARI may overestimate or underestimate risk under certain environmental scenarios.

Research indicates that while the fungus can grow between 28°C and 33°C, aflatoxin levels peak at 33-35°C

Table 2: Risk levels for ARI in maize across Albania's main producing regions.

Region	Mean ARI (%)	Max ARI (%)	Risk level
Elbasan	58.99	68.20	High
Fier-Lushnja	55.94	73.85	High
Gjirokastër	52.40	72.31	High
Shkodër	45.22	66.67	Moderate-High
Durrës	39.4	63.60	Low-Moderate
Korçë	10.72	24.62	Low

(Table 3). Temperatures below 30°C may support fungal growth but result in significantly lower toxin levels. Conversely, temperatures above 35°C typically hinder fungal growth, although some toxins may persist. Thus, this value serves as a practical, scientifically supported cutoff for identifying days at high risk of contamination. Lower thresholds, such as 30°C or 32°C, could overstate the risk by including days less conducive to substantial aflatoxin production (Cotty and Jaime-Garcia, 2007).

Albania's emerging mycotoxin crisis in the balkan context

While Albania has received less scientific attention than neighboring Serbia, Romania and Croatia, preliminary evidence suggests similar, if not escalating, mycotoxin challenges. Topi *et al*. (2021, 2023, 2024) have documented the presence of *Fusarium mycotoxins, Aspergillus* and *Penicillium toxins* in Albanian cereals, with recent studies (Mato *et al*., 2024a) revealing high prevalence of mycotoxigenic fungi and AFB1 contamination in corn and wheat.

Our climate-based risk assessment provides crucial context for interpreting these contamination surveys. The high ARI values observed in western regions during specific years (*e.g*., 2015, 2017) predict elevated aflatoxin risk and help explain temporal variations in observed contamination data. Conversely, consistently low ARI in Korçë predicts this region should show fewer aflatoxin problems- a hypothesis that could be tested in future field surveys.

The downstream impacts of the food chain are already evident: Tahiri *et al*. (2025) recently documented aflatoxin (AFM1) contamination in milk consumed in Tirana, indicating that field-level aflatoxin contamination is translating into animal feed contamination and human exposure *via* dairy products. This underscores the urgency of our findings-climate-driven mycotoxin risks are not merely agricultural problems but human health threats that require integrated policy responses.

Agricultural adaptation in high-risk regions

Our identification of western lowland regions as high-risk zones suggests the need for targeted agronomic interventions. While our study does not directly test mitigation strategies, the literature (Dövényi-Nagy *et al*., 2020; Medina *et al*., 2014) supports the promotion of heat- and drought-tolerant maize varieties in Fier-Lushnjë, Durrës and Elbasan. Expansion of irrigation infrastructure to mitigate drought stress, which exacerbates fungal infection and aflatoxin accumulation. Adjustment of planting dates to shift flowering away from peak heat (June rather than July in some regions). Implementation of integrated pest management to reduce insect damage, a co-risk factor for *A. flavus* colonization. In contrast, Korçë's low ARI status suggests it may become increasingly valuable for certified low-contamination maize production, with potential for premium market positioning. Our analysis of ARI trends over 2004-2024 reveals a clear upward trajectory in high-risk conditions, with western regions frequently exceeding ARI thresholds of 60% or more in recent years. This temporal pattern is consistent with broader climate warming trends documented for Southern Europe and the Balkans, which have experienced accelerated temperature increases exceeding global averages (Battilani *et al*., 2016; Dövényi-Nagy *et al*., 2020).

Dövényi-Nagy *et al*. (2020), in their comprehensive review of pre-harvest aflatoxin modeling in changing climates, found that Eastern and Central European regions are experiencing a gradual expansion of climatic conditions conducive to aflatoxin production. Our data suggest that Albania is at the center of this expansion zone. Specifically, the frequency of extreme heat years (defined as years with ARI >60% in multiple regions) has increased in the most recent decade (2015-2024) compared to the earlier period (2004-2014). Critical-window analysis (July-August) confirms that mid-summer heat stress, identified by Cotty and Jaime-Garcia (2007) as the primary driver of aflatoxin biosynthesis, has intensified. This temporal pattern aligns with documented extreme heat events in the Balkans (*e.g*., 2015, 2017, 2022 heat waves), which have been linked to substantial aflatoxin outbreaks in neighboring countries (Kos *et al*., 2018; Topi *et al*., 2023).

While this study contributes valuable regional insights, several limitations must be acknowledged and addressed in future work. Our ARI model relies exclusively on temperature, omitting critical drivers of aflatoxin production, such as relative humidity and rainfall. Soil conditions, such as soil moisture, pH and nutrient status, also influence both maize stress tolerance and fungal proliferation. These soil-level variables were not captured. Agricultural practices: Irrigation, variety selection, pesticide use and harvest timing substantially modify actual field-level risk. Postharvest conditions: Storage temperature, humidity control and pest management affect postharvest contamination dynamics, which are not reflected in the growing season ARI. Dövényi-Nagy *et al*. (2020) emphasized that integration of moisture and agronomic

Table 3: Critical temperature thresholds.

Parameter	Critical value	Biological effect
A. flavus: Optimal growth	28-33°C	Active fungal growth
Maximum aflatoxin production	33-35°C	Intensive toxin production
The growth is limited	>35°C	Reduced growth, possible toxin presence
The growth is minimal	<20°C	Low or halted activity

Source: Medina *et al*. (2014).

data typically improves model performance by 15-40%. Future Albanian studies should incorporate these variables to enhance predictive power.

CONCLUSION

This study demonstrates that rising temperatures associated with climate change are significantly increasing the climatic suitability for aflatoxin contamination in maize across Albania. The application of a temperature-based Aflatoxin Risk Index (ARI) revealed clear spatial and temporal patterns, with western lowland regions consistently exhibiting higher risk levels than inland areas. The findings highlight a growing vulnerability of national food systems to climate-driven mycotoxin contamination, particularly during critical crop development stages in mid-summer. The proposed ARI provides a practical and scalable tool for preliminary risk assessment, especially in data-limited contexts.

However, the model's reliance on temperature alone represents a limitation and future research should integrate additional environmental and agronomic variables to enhance predictive accuracy. Strengthening monitoring systems and implementing targeted mitigation strategies will be essential to reduce aflatoxin risks and ensure food safety under evolving climatic conditions.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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