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Climate and Storage Conditions as Drivers of Fungal Contamination and Mycotoxin Production in Food Products: Systematic Review Article

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ABSTRACT

Food safety remains a major global concern due to the potential contamination of food products with fungi and their associated Mycotoxins. Fungal contamination can occur at different stages of the food chain, including production, processing, storage, and distribution. Environmental factors such as temperature, relative humidity, and water activity play an important role in promoting fungal growth and stimulating mycotoxin production. Improper storage conditions may further increase the risk of fungal proliferation and subsequent toxin accumulation in food commodities.

This review discusses the major fungal genera commonly associated with food contamination, including Aspergillus, Penicillium, and Fusarium, and highlights their capacity to produce significant Mycotoxins such as aflatoxins, Ochratoxin, and Fumonisins. The article also summarizes the main environmental conditions that influence fungal development in food products and reviews current strategies used to reduce fungal contamination and Mycotoxin formation during storage and handling.

Understanding the relationship between environmental conditions, storage practices, and fungal contamination is essential for improving food safety and minimizing the health risks associated with Mycotoxin exposure.

الظروف المناخية وظروف التخزين كعوامل مؤثرة في تلوث المنتجات الغذائية بالفطريات وإنتاج السموم الفطرية.

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المُخلص

لا تزال سلامة الغذاء تمثل قضية عالمية رئيسية نظرًا لاحتمالية تلوث المنتجات الغذائية بالفطريات وما يرتبط بها من سموم فطرية (Mycotoxins). ويمكن أن يحدث التلوث الفطري في مراحل مختلفة من السلسلة الغذائية، بما في ذلك الإنتاج، والمعالجة، والتخزين، والتوزيع. وتلعب العوامل البيئية مثل درجة الحرارة، والرطوبة النسبية، ونشاط الماء دورًا مهمًا في تعزيز نمو الفطريات وتحفيز إنتاج السموم الفطرية. كما أن ظروف التخزين غير المناسبة قد تزيد من خطر تكاثر الفطريات وتراكم السموم في السلع الغذائية.
تستعرض هذه المقالة الأجناس الفطرية الرئيسة المرتبطة عادةً بتلوث الأغذية، بما في ذلك Aspergillus وPenicillium وFusarium، مع إبراز قدرتها على إنتاج سموم فطرية مهمة مثل الأفلاتوكسينات والأوكراتوكسينات والفومونيسينات. كما يلخص هذا الاستعراض أهم الظروف البيئية التي تؤثر في نمو الفطريات في المنتجات الغذائية، ويستعرض الاستراتيجيات الحالية المستخدمة للحد من التلوث الفطري وتكوين السموم الفطرية أثناء التخزين والتداول.

إن فهم العلاقة بين الظروف البيئية وممارسات التخزين والتلوث الفطري يُعد أمرًا أساسيًا لتحسين سلامة الغذاء وتقليل المخاطر الصحية المرتبطة بالتعرض للسموم الفطرية.

الكلمات المفتاحية: التلوث الفطري , السموم الفطرية , سلامة الغذاء , التغير المناخي , ظروف التخزين , أدارة ما بعد الحصاد .

1 Introduction

Food safety is a major global public health concern due to its direct impact on human health and nutritional well-being. Food products may become contaminated at various stages of the food supply chain, including production, harvesting, processing, storage, transportation, and marketing. Among the different types of contamination, fungal contamination represents one of the most significant threats to food quality and safety. Fungal growth can lead to spoilage of food products and the production of toxic secondary metabolites known as mycotoxins, which may pose serious health risks to humans and animals (Bennett & Klich, 2003; Pitt & Hocking, 2009; Khan et al., 2024).

Fungal contamination in food commodities is strongly influenced by environmental and climatic factors.

Parameters such as temperature, relative humidity, and rainfall patterns play important roles in determining fungal growth and the production of mycotoxins. Mycotoxins such as aflatoxins, ochratoxin A, fumonisins, and deoxynivalenol are among the most common toxins associated with food contamination and are known for their toxic, carcinogenic, and immunosuppressive effects (Bennett & Klich, 2003; Medina et al., 2017; Khan et al., 2024).

Several fungal genera are commonly associated with mycotoxin contamination in food products, particularly Aspergillus, Fusarium, and Penicillium. These fungi frequently contaminate cereals, nuts, spices, and dried fruits during both pre-harvest and post-harvest stages. Environmental conditions such as temperature, water activity, and relative humidity play a crucial role in regulating fungal growth and mycotoxin biosynthesis. Under favorable conditions, these factors can significantly increase fungal colonization and toxin production in food commodities (Magan et al., 2010; Garcia-Cela et al., 2015; Miliordos et al., 2025).

Post-harvest storage conditions also play a critical role in the development of fungal contamination and mycotoxin production. Poor storage practices, including high moisture levels, inadequate ventilation, and prolonged storage periods, can promote fungal growth and increase the risk of mycotoxin accumulation in stored products. Proper storage management and hygiene practices are therefore essential to reduce contamination risks and maintain food quality (FAO, 2011; Kumar & Kalita, 2017; Walker et al., 2018).

Climate change is expected to further influence fungal ecology and mycotoxin contamination patterns in food systems. Rising temperatures, altered rainfall patterns, and extreme weather events may facilitate the spread of toxigenic fungi and affect their geographical distribution. As a result, climate change may increase the occurrence of mycotoxin contamination in various food commodities and pose additional challenges for food safety and public health worldwide (Battilani et al., 2016; Medina et al., 2014; Moretti et al., 2019; Casu et al., 2024).

Therefore, this review aims to examine the influence of climate factors and storage conditions on fungal contamination and mycotoxin production in food products, and to highlight the key environmental parameters that contribute to their occurrence and distribution.

2 Materials and Methods

This study was conducted as a systematic literature review following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to identify, screen, and analyze published studies related to the influence of climatic factors and storage conditions on fungal contamination and Mycotoxin production in food products.

2.1 Literature Search Strategy

A systematic search was performed in major scientific databases, including PubMed, Scopus, and Web of Science, covering publications from 2010 to 2025.

The following structured search strings were applied using Boolean operators (AND,OR):

“fungal contamination” AND “food products” AND “Mycotoxins-”

“Aspergillus” OR “Fusarium” OR “Penicillium” AND “storage conditions-”

“climate change” AND “temperature” AND “humidity-”

“water activity” AND “fungal growth” AND “food safety-”

“post-harvest” AND “storage” AND mycotoxins

Search strategies were adapted according to the syntax of each database to ensure comprehensive retrieval of relevant studies.

Study Selection Process (PRISMA)2.2

All retrieved records were imported into a reference management system, and duplicate studies were removed prior to screening.

The selection process followed the PRISMA framework and included four stages:

1.Identification of records through database searching

2.Screening of titles and abstracts

3. Eligibility assessment through full-text review

4. Inclusion of studies meeting all criteria

Only studies that fulfilled the eligibility criteria were included in the final analysis.

A PRISMA flow diagram (Figure 1) was used to illustrate the study selection process

2.3 Eligibility Criteria

Studies were included if they met the following criteria:

- Published in English between 2010 and 2025

-Peer-reviewed original research articles, systematic reviews, or official reports

-Focused on fungal contamination, Mycotoxin production, climate factors, or storage conditions in food commodities

Studies were excluded if they were:

Conference abstracts, editorials, or non-peer-reviewed publications-

-Lacking sufficient data on environmental or storage variables

-Duplicates or irrelevant to the research objectives

2.4 Quality Assessment

The methodological quality of the included studies was evaluated using a structured qualitative assessment based on:

-Clarity of study design

-Adequacy of sample size

-Reliability of analytical methods

-Relevance of climatic and storage variables

Studies with insufficient methodological information were excluded from interpretation to ensure data reliability and consistency.

2.5 Data Extraction and Analysis

A total of approximately 45 studies were included in the final analysis.

Data extracted from each study included:

-Type of food product

-Fungal species identified

-Environmental conditions (temperature, relative humidity, and water activity)

-Storage conditions (duration, ventilation, and packaging)

-Reported Mycotoxin occurrence

-A qualitative thematic synthesis approach was used to summarize and interpret the findings of the included studies (Thomas & Harden, 2008).

The selected studies were grouped into major thematic categories based on the environmental and storage variables investigated. These themes included temperature effects, humidity and water activity, climate change impacts, and storage practices influencing fungal growth and Mycotoxin production in food products.

Patterns, consistencies, and differences among the reviewed studies were analyzed to provide an integrated interpretation of the findings

Figure 1. PRISMA Flow Diagram of Study Selection Process

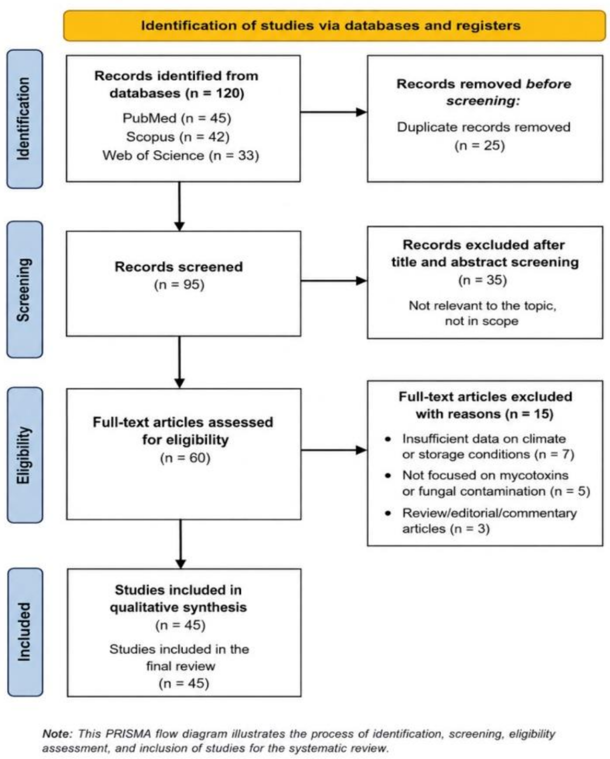

Figure 1 . PRISMA flow diagram of the study selection process, showing identification, screening, eligibility assessment, and inclusion of studies in the systematic review.

3 Results

3.1 Effect of Temperature

Temperature was identified as a key environmental factor influencing both fungal growth and Mycotoxin production in food commodities. Several studies reported that moderate to high temperatures enhance the metabolic activity of toxigenic fungi such as Aspergillus and Fusarium, thereby increasing the risk of Mycotoxin accumulation in products such as cereals, nuts, and dried fruits (Casu et al., 2024; Khan et al., 2024).

Evidence from the reviewed literature indicates that temperatures between 25–35 °C are generally considered optimal for the growth of many toxigenic fungal species. Under these conditions, fungal colonization can occur rapidly during storage, particularly when temperature is combined with high moisture levels.

However, temperature alone does not fully determine Mycotoxin production. Several studies indicate that toxin biosynthesis depends on complex interactions between temperature, water activity, and nutrient availability. Consequently, favorable temperatures may support fungal growth even when toxin production remains limited.

3.2Effect of Humidity and Water Activity

Relative humidity and water activity play a crucial role in regulating fungal contamination and toxin production. Most filamentous fungi can grow at water activity (aw) values above 0.80, while optimal Mycotoxin production generally occurs at aw values above 0.90 (Miliordos *et al.*, 2025).

High relative humidity, particularly values exceeding 70%, promotes moisture accumulation in food products and facilitates fungal colonization during storage. Improper moisture control has been widely reported as a major factor contributing to contamination in dried fruits, grains, spices, and other stored food commodities.

Nevertheless, fungal growth and Mycotoxin production do not always occur simultaneously. In some cases, fungi may develop under moderately favorable environmental conditions while toxin production remains undetectable due to insufficient environmental stress or suboptimal metabolic conditions.

The main environmental parameters influencing fungal development and Mycotoxin biosynthesis are summarized in Table 1

Table 1. Effect of environmental factors on fungal growth and mycotoxin production.

Environmental factor	Typical range	Effect on fungal growth	Effect on mycotoxin production
Temperature	25–35 °C	Optimal growth of Aspergillus and Fusarium	Enhanced toxin synthesis (Khan et al., 2024)
Relative humidity	>70%	Promotes fungal colonization	Higher aflatoxin and fumonisin levels (Casu et al., 2024)
Water activity (aw)	>0.90	Rapid fungal proliferation	Optimal conditions for Mycotoxin production (Miliordos et al., 2025)

3.3 Impact of Climate Change

Climate change has emerged as an important driver influencing fungal ecology and the distribution of Mycotoxin-producing species. Rising global temperatures, altered rainfall patterns, and extreme weather events have been associated with the expansion of toxigenic fungi into new geographical regions (Casu et al., 2024).

These environmental changes may shift the balance between crop hosts and fungal pathogens. Warmer climates may favor thermo tolerant fungi such as Aspergillus, while increased humidity may facilitate fungal infection during crop development and storage.

In addition, extreme weather events may damage crops and create favorable entry points for fungal colonization, thereby increasing the risk of contamination during post-harvest storage.

The projected influence of climate-related factors on fungal contamination and food safety is summarized in Table 2

Table 2. Impact of climate change on fungal contamination and food safety.

Climate change factor	Impact on fungi	Food commodities affected	Reference
Rising temperature	Enhanced growth of toxigenic fungi	Cereals, nuts	Casu et al. (2024)
Altered rainfall patterns	Increased moisture stress and infection	Maize, wheat	Khan et al. (2024)
Extreme weather events	Higher post-harvest contamination risk	Stored grains and dried fruits	Miliordos et al. (2025)

3.4 Storage Practices and Mycotoxin Risk

Storage conditions play a critical role in determining the level of fungal contamination and Mycotoxin accumulation in food products. Poor ventilation, prolonged storage duration, and improper packaging have been widely identified as major contributors to fungal growth in stored food commodities (Khan *et al.*, 2024; Miliordos *et al*., 2025).

Conversely, improved storage management practices, including hermetic storage systems, moisture control, and appropriate packaging materials, can significantly reduce the risk of contamination and enhance food safety (Kumar & Kalita, 2017; Walker *et al*., 2018; FAO, 2011).

Interestingly, some studies reported fungal growth without detectable Mycotoxins, as observed in the study of Miliordos *et al*. (2025). This phenomenon may occur when environmental conditions are sufficient to support fungal colonization but are not optimal for toxin biosynthesis. Mycotoxin production is often triggered by specific environmental stresses; therefore, the presence of fungi does not necessarily indicate toxin contamination.

The integration of findings from different geographic regions and food commodities is summarized in

Table 3

Table 3. Integration of Local and Global Evidence on Fungal Contamination

Study	Food Product	Main Fungal Species	Climate / Storage Factors	Key Findings
Abdalrazig & El-Alwany (2025)	Dried fruits	*Aspergillus flavus, A. niger*	Warm climate, open market storage	High fungal prevalence; Aflatoxigenic strains detected
Khan *et al.* (2024)	Cereals, nuts	*Aspergillus spp.*	High temperature, poor storage	Enhanced fungal growth and mycotoxin risk
Casu *et al.* (2024)	Maize, wheat	*Aspergillus, Fusarium*	Climate change, rising temperature	Expansion of toxigenic fungi
Miliordos *et al.* (2025)	Dried fruits	*Aspergillus, Penicillium*	High humidity, long storage	Fungal growth without detectable toxins

4 Discussion

Temperature, relative humidity, and water activity are widely recognized as critical determinants of fungal growth and Mycotoxin production in food commodities. Moderate to high temperatures (25–35 °C) enhance the metabolic activity of toxigenic fungi such as Aspergillus and Fusarium, resulting in increased fungal colonization and potential Mycotoxin accumulation in cereals, nuts, and dried fruits (Casu et al., 2024; Khan et al., 2024). However, the relationship between fungal presence and toxin production is not always direct, as Mycotoxin biosynthesis is regulated by complex environmental and physiological interactions.

A notable finding in this review is the discrepancy observed in the Ajdabiya study (Abdalrazig & El-Alwany, 2025), where Aflatoxigenic fungi were detected, yet no aflatoxins were identified using the lateral flow immunoassay (LFIA). This inconsistency may be explained through multiple competing interpretations. First, methodological limitations may have influenced the results, as LFIA techniques generally have lower sensitivity and reduced quantitative accuracy compared to chromatographic methods such as HPLC and LC–MS/MS, potentially leading to false-negative results at low toxin concentrations.

Second, environmental and ecological conditions may have supported fungal growth without activating toxin biosynthesis. mycotoxin production depends on specific physiological triggers, including water activity, oxygen availability, substrate composition, and storage duration. Under suboptimal or non-stress conditions, fungi may remain metabolically active without producing detectable levels of toxins.

Third, the presence of confounding variables across studies must be considered. Variations in sampling procedures, storage environments, pre-harvest contamination levels, and detection methodologies contribute significantly to heterogeneity in reported outcomes, making direct comparison between studies challenging.

In addition, climate change is expected to intensify fungal contamination risks by altering temperature and humidity patterns, thereby expanding the ecological range of toxigenic fungi into new geographical regions (Casu et al., 2024). However, the interaction between climate variables, storage practices, and fungal metabolism remains complex and requires further investigation to distinguish correlation from causation in Mycotoxin occurrence.

Proper storage conditions, including moisture control, ventilation, and hermetic packaging, remain essential in reducing fungal proliferation and toxin formation (Kumar & Kalita, 2017; Walker et al., 2018; FAO, 2011). Overall, both global and regional evidence highlight that fungal contamination is influenced by a multifactorial system rather than single environmental drivers..

5 Conclusions

Fungal contamination and Mycotoxin production in food commodities are strongly influenced by environmental factors, particularly temperature, relative humidity, and water activity, as well as post-harvest storage practices. Moderate to high temperatures and elevated moisture levels promote fungal proliferation, especially of Aspergillus and Fusarium species, while inadequate ventilation, prolonged storage, and improper packaging further increase contamination risks.

Evidence from both global studies and the regional case of Ajdabiya (Abdalrazig & El-Alwany, 2025) demonstrates that the presence of toxigenic fungi does not always result in detectable Mycotoxin production. This highlights the critical role of environmental stress conditions, metabolic regulation, and storage duration in determining toxin biosynthesis.

Climate change represents an additional driving force that may alter fungal ecology, expand the geographical distribution of toxigenic species, and increase contamination risks in previously low-risk regions. These combined factors emphasize that fungal contamination is a dynamic and multifactorial process influenced by both environmental and anthropogenic conditions.

Future research should focus on standardizing analytical methodologies, particularly for Mycotoxin detection, and implementing longitudinal studies to better understand temporal trends under changing climatic conditions. Strengthening integrated food safety strategies, including improved storage technologies and environmental monitoring, is essential for reducing fungal contamination and ensuring safer and more resilient food supply chains.

Conflict of interest: The authors declare that there are no conflicts of interest

Ethics:

This study is a review article based on previously published data , therefore ethical approval was not required.

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