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Mycotoxins Occurrence and Mycotoxigenic Fungi in Imported Dried Farm Produce under Simulated Storage Conditions in Qatar

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Abstract

Climate change is increasingly recognized as a key driver of the proliferation of mycotoxigenic fungi and the production of mycotoxins, posing significant risks to global food safety. This study addresses a critical research gap in arid and semi-arid regions, specifically the Gulf, using exploratory experimental investigation of imported dried farm produce sold in the State of Qatar to provide context-specific insights into mycotoxin occurrence in imported dry food products. A total of 41 samples of grains, nuts, and spices were collected from Qatari retail outlets and monitored under simulated storage conditions, averaging 19.4°C and 63.6% relative humidity. Samples were analyzed using ultra-high-performance liquid chromatography–tandem mass spectrometry (UHPLC–MS/MS) to detect aflatoxins and ochratoxin A. Microbiological analysis revealed the presence of several fungal genera, including Aspergillus, Penicillium, and Cladosporium, as early as the first week of sampling. Quantitative analysis using UHPLC–MS/MS confirmed that 27% (11 of 41) of the samples contained detectable levels of Aflatoxins (AFT) or Ochratoxin A (OTA). Notably, turmeric showed consistent co-occurrence of AFT and OTA across batches, indicating it is a high-risk commodity. While all detected concentrations remained within European Union regulatory limits, significant variability was observed between sourcing locations, with local shops and souqs (Batch 3) showing the highest frequency of contamination. The results demonstrate that even moderate storage conditions (19–

24°C) in arid climates can support fungal activity and toxin biosynthesis. These findings underscore the importance of comprehensive supply chain oversight and the development of adaptive food safety frameworks to mitigate the risks associated with cumulative dietary exposure and climate-driven fungal shifts.

Keywords: Mycotoxin; Fungi; Food Safety; Dry Produce; Climate Change

1.0 Introduction

Climate change is significantly impacting food security, especially in areas with high humidity, high rainfall, floods, hurricanes, or droughts. Beyond damaging agricultural land, climate change can alter crop susceptibility to pathogenic organisms, particularly mycotoxigenic fungi, by creating environmental conditions that favor fungal growth and thus mycotoxin production (Van der Fels-Klerx et al., 2019; Lee et al., 2019; Bogach et al., 2024; Platzer et al., 2025). Mycotoxins, toxic metabolites produced by certain fungi, are a major natural global contaminant threatening food safety due to their widespread occurrence and severe health risks (Medina et al, 2015; Perrone, 2020; Koss et al, 2023). Increased carbon dioxide levels, elevated temperatures, high humidity, and extreme rainfall all promote the growth of mycotoxigenic fungi, such as Aspergillus, Fusarium, and Penicillium (Kos et al, 2023; Daou et al, 2021; Zingales et al, 2022; European Food Safety Authority, 2024). Those produce harmful mycotoxins, including aflatoxins (AF), deoxynivalenol (DON), zearalenone (ZEN), and ochratoxin A (OTA) (European Food Safety Authority, 2024; Battilani et al, 2016; Moretti et al, 201; Sundheim et al, 2015; European Environment Agency, 2024), whether in agricultural fields or on stored foods on shelves (El-Sayed et al, 2022). As climate change continues to shift temperature and precipitation patterns, the likelihood of fungal infections and toxin accumulation in crops is expected to rise, posing serious challenges to global food security. Rising global temperatures favor the growth of mycotoxigenic fungi such as Aspergillus (aflatoxins, ochratoxin A) in tropical regions and Penicillium (ochratoxin A, patulin) in temperate zones. Research shows that elevated CO_2 levels, drought, and higher temperatures significantly increase aflatoxin B1 (AFB1) production, which is linked to increased expression of biosynthetic genes (Zingales et al, 2022). Climate models predict earlier flowering, shorter growing seasons, and the expansion of maize cultivation northward in Europe. The AFLA-maize model forecasts higher aflatoxin contamination under a +2°C warming scenario, especially in Spain, Italy, and the Balkans. Under a +5°C scenario, contamination zones

expand further, although AFB1 levels are lower than in the +2°C scenario (Van der Fels-Klerx et al, 2019). These changes increase contamination risks, affecting both food safety and agricultural productivity. Without a solid foundation of food security, food safety will remain a challenge for many individuals worldwide (World Food Summit, 1996).

Mycotoxins can enter the food chain directly through contaminated plant-based ingredients or indirectly via fungal growth on food. They can accumulate in crops during field growth, during harvesting, during transportation, or after processing, packaging, and storage (El-Sayed et al, 2022). Additionally, climate change, particularly rising global temperatures, has worsened crop diseases, increasing reliance on pesticides. This not only increases the risk of mycotoxin contamination but also adds to the overall human health burden (Dean et al., 1987; Pallarés et al., 2022; Tirado et al., 2010). Exposure to mycotoxins has been linked to hepatotoxicity, nephrotoxicity, neurotoxicity, mutagenicity, carcinogenicity, and immunosuppression (Moretti et al., 2019; Greeff-Laubscher et al., 2020; Khan et al., 2024; Dean et al., 1987). Aflatoxins, primarily produced by *Aspergillus flavus* and *A. parasiticus*, are known to contaminate cereals, nuts, and spices. These toxins are particularly dangerous due to their association with fatal liver damage and an increased risk of liver cancer (World Health Organization, 2018). Ochratoxin A, produced by both *Aspergillus* and *Penicillium* species, is commonly found in cereals, coffee, and dried fruits. It can lead to kidney toxicity, immunosuppression, and developmental harm. *Fusarium* species produce a range of toxins such as trichothecenes and fumonisins, which affect crops like wheat, oats, and maize. These toxins have been linked to skin irritation, diarrhea, infertility, and liver and kidney toxicity. Additionally, patulin, another mycotoxin produced by Aspergillus and Penicillium, is typically found in spoiled fruits and grains and is associated with immune toxicity and gastrointestinal illness (World Health Organization, 2018). Building on these exposure pathways, growing evidence indicates that climate-related stressors amplify mycotoxin risks across multiple stages of the food supply chain. At the pre-harvest stage, early

harvesting has been shown to significantly reduce aflatoxin levels in peanuts under drought conditions (Martins et al, 2023), illustrating how heat and water stress weaken plant defense mechanisms and facilitate fungal invasion. As climate change intensifies, these stressors render certain crops increasingly vulnerable to contamination. Beyond the field, post-harvest handling represents a critical control point, as fungal proliferation and toxin production can continue during storage. Key determinants of contamination include temperature regulation, moisture control, storage materials, and storage duration (Magembe et al, 2016). For example, in Tanzania, maize stored directly on the floor exhibited elevated levels of *Fusarium* toxins due to moisture condensation, whereas the use of ventilated cribs and natural antifungal agents, such as wood ash and neem leaves, reduced fungal contamination in both maize and groundnuts (Magembe et al, 2016). Similarly, improper drying and storage practices in Brazil have been linked to aflatoxin contamination in Brazil nuts and ochratoxin A (OTA) contamination in coffee and cocoa (Taniwaki et al, 2019). Fungal ecology further influences contamination dynamics, as pathogens display substrate-specific nutrient preferences. *Fusarium graminearum*, for instance, preferentially utilizes wheat glutenin, increasing the susceptibility of wheat-based products. This vulnerability extends to post-harvest processing stages such as milling and malting, where continued environmental exposure affects the redistribution and concentration of mycotoxins in final products (Wawrzyniak et al., 2021b; Zhang et al., 2019; Kochiieru et al., 2019; Malachova et al., 2010). Experimental evidence supports these observations, with DON levels in stored wheat increasing over 30 weeks at 25°C and 75% relative humidity (Zhang et al, 2019), and rapid mold growth in barley occurring within 48 hours when water activity (a_t) exceeded 0.92, while lower a_t values (<0.80) delayed fungal proliferation (Wawrzyniak et al, 2012b). Comparable temperature-dependent effects have been reported in dried produce. To prevent aflatoxin formation in dried figs, drying at temperatures above 30°C followed by storage below 10°C has been recommended (Galván et al, 2021). Likewise, *Aspergillus nomius*, a major aflatoxin producer in Brazil

nuts, exhibits increased aflatoxin production at mild post-harvest temperatures of approximately 25°C (Yunes et al, 2019).

Qatar's heavy reliance on imported food raises concerns about exposure to mycotoxins. In 2019, nuts and spices marketed in Qatar contained aflatoxin levels of 534.15 ng/g and 371.6 ng/g, respectively (Al Jabir et al, 2019). Dietary exposure assessments indicated that ochratoxins and fumonisins may exceed tolerable daily intake (TDI) levels. Many contaminated spices originate from tropical regions, where warm temperatures and high humidity favor fungal growth and mycotoxin production (Hammami et al, 2014). Cereals are mainly imported from India (38%) and Russia (13%), while the United Arab Emirates is the primary supplier of coffee, tea, mate, and spices (36%), followed by India (21%). Elevated aflatoxin B1 (AFB1) levels have also been reported in products imported from Pakistan, India, and China, as well as in locally available foods (Al Jabir et al, 2019). Human biomonitoring data further confirm exposure. In 2021, mycotoxins were detected in 37% of serum samples and in fewer than 20% of urine samples, with 88% of positive samples containing a single mycotoxin and 12% showing co-exposure. Trichothecenes and zearalenone metabolites were most frequently detected, followed by aflatoxins, roquefortine C, and mycophenolic acid (AlJaal, 2021).

Although global evidence increasingly demonstrates the impact of climate change on the food supply chain, data specific to Qatar remain limited. Given the country's heavy reliance on imported foods, enhanced surveillance of mycotoxin contamination is essential. Accordingly, this study aims to assess the prevalence and profiles of mycotoxins in dry produce marketed in Qatar and to explore the potential influence of climate-related factors on fungal growth and mycotoxin production. To address this aim, an in-depth literature review was conducted to synthesize global evidence on climate change–driven fungal proliferation and mycotoxin formation. In parallel, a microbial and analytical assessment was performed on selected ready-to-eat dried grains, pulses, and nuts sold in high-street retail outlets in Qatar to identify fungal species and quantify associated mycotoxin levels.

2.0 Materials and Methods

2.2 Experimental Methodology

Forty-one (41) readily available dried produce items were purchased (January-February, 2025) from randomly selected high-street shops and open markets (souqs) across three highly populated municipalities in Qatar: Doha, Al Rayyan, and Al Wakrah (Table 1). The selected products were commonly consumed dried foods, including legumes, grains, nuts, seeds, and spices. Samples were sourced from ten local and regional manufacturers, ensuring diversity in origin and processing conditions. All samples were within their labeled shelf-life (use-by or best-before dates) at the time of purchase. The selection of the farm produce for the study was based on product availability, consumption among divers groups resident in Qatar and reported contamination incidence in dry, subtropical climate.

Table 1. Sample Selection of Dried Produce and their Expiry Dates

	Batch 1	Expiry Date	Batch 2	Expiry Date	Batch 3	Expiry Date
1	White eye beans	2026	Chickpea	2027	Cashew	NA
2	Fenugreek	2026	Cummin	2027	Almond	01/2026
3	Foul Bean	11/2026	Turmeric	2027	Peanuts	11/2026
4	Moong dal (green gram)	04/2026	Soya chunks	2025	Chia seeds	05/2026
5	Sesame seeds roasted	12/2025	Popcorn	2027	Lentil	NA
6	Cashew nuts	2026	Almond	2026	Black pepper	NA
7	Chickpea	11/2026	Lentil	2027	Paprika	2027
8	Mix Spices	2027	Moong whole	04/2026	Kalonji Seed	NA
9	Lentil	2026	Black eye bean	01/2027	Rice (par-boiled)	NA
10	Chana dal (chickpea)	2026	Cardamon	06/2025	Arabic coffee	NA
11	Almond	2026	Chana dal (chickpea)	02/2027	Fenugreek	NA
12	Black eye bean	2025	Sesame seeds	05/2026	Turmeric	NA
13	Black Pepper	2026	Black pepper	2027	Chickpea	2027

2.2.1 Environmental Monitoring of Selected Food Samples

To simulate typical retail storage conditions and assess their potential impact on fungal proliferation, all samples were stored at room temperature for 1 month. Environmental parameters, including temperature (°C) and relative humidity (%)**,** were continuously monitored using a TULATEC T2 data logger, with measurements recorded every 15 minutes. The collected data were exported in CSV format and used to characterize storage conditions and support the interpretation of fungal growth and mycotoxin findings.

2.2.2. Microscopy analysis of fungi isolates

Selected dried produce samples were purchased from high street shops and the open market (Souq). All samples at the time of conducting the research were within the expiry date stated on the packaging materials (Table 2). From each product, approximately 2 grams of pulverized sample were reconstituted into 5 ml of deionized water, stirred, and allowed to stand for 10 min and 100µl from each sample transferred onto two selected media Potato Dextrose Agar-PDA and Malt Extract Agar-MEA (Himedia, India) in triplicate and incubated at 23 °C for 4-7 days or until visible growth appears on the plates thereafter. Isolates were sub-cultured further on selected agar plates for identification based on growth morphology, colony characteristics, and microscopic examination. The slide culture method was used to prepare fungal isolates. A humid environment was created using cotton wool soaked in distilled water, with skewer sticks as a base for easy lifting. A thin block of agar (1x1 cm) was placed on a microscope slide, and isolates from the fungal colony were carefully spread around each angle using an inoculation loop. A coverslip was placed on each and incubated until growth was sufficient (Figure 2). Coverslips were removed, the fungus strain was attached, stained with lactophenol-cotton blue (LPCB) (Himedia, India), placed on a new cover slide, and viewed under the microscope.

2.2.3 UHPLC–MS/MS Analysis

For each of the 41 samples purchased from different retail outlets in Qatar, 5.0 ± 2.0 grams of the homogenized sample was processed in a 50 mL centrifuge tube. Each sample was diluted with 20 mL of extraction solvent (80% methanol/DIW), vortexed for 2–3 minutes, and after which the QuEChERS kit contents were added. The mixture was agitated and then centrifuged for 10 minutes at 4700 r/min. The supernatant from each sample was transferred into a UHPLC vial using a 3 mL or 5 mL syringe fitted with a PVDF 0.22 μm syringe filter. Subsequently, 50.0 μL of ISTD mix solution was added to a separate 1.5 mL ultra-high-performance liquid chromatography (UHPLC) vial, the mixture was brought to a final volume of 1 mL with 950.0 μL of the sample supernatant, and the mixture was mixed thoroughly. Samples were then analyzed using an Agilent 6470A LC–MS/MS system equipped with an Agilent 1290 UHPLC, operating under the conditions described in Table 2. Gradient elution with deionized water and methanol was applied during sample analysis. For mycotoxin calculation, mycotoxin concentrations were determined using a 7-level calibration curve (peak area versus concentration) for quantitation. A correlation coefficient shall be ≥ 0.99 (Figures 1 and 2).

Table 2. UHPLC Instruments Operating Conditions

Column	Agilent ZORBAX Eclipse XDB - C-18, 4.6 ×150 mm, particle size 5 μm.
Column temperature	35 ºC
Flow rate	0.6 mL / min.
Mobile phase (two bottles)	Component (A): Deionized Water: Ammonium formate (5 mM): Formic acid (0.2 %). Component (B): Methanol: Ammonium formate (5 mM): Formic acid (0.2 %).

Descriptive statistical analysis was performed to summarize the occurrence and concentration of mycotoxins across the sampled products. Environmental parameters, including temperature and relative humidity, were analyzed to characterize storage conditions and examine their potential association with fungal growth and mycotoxin presence.

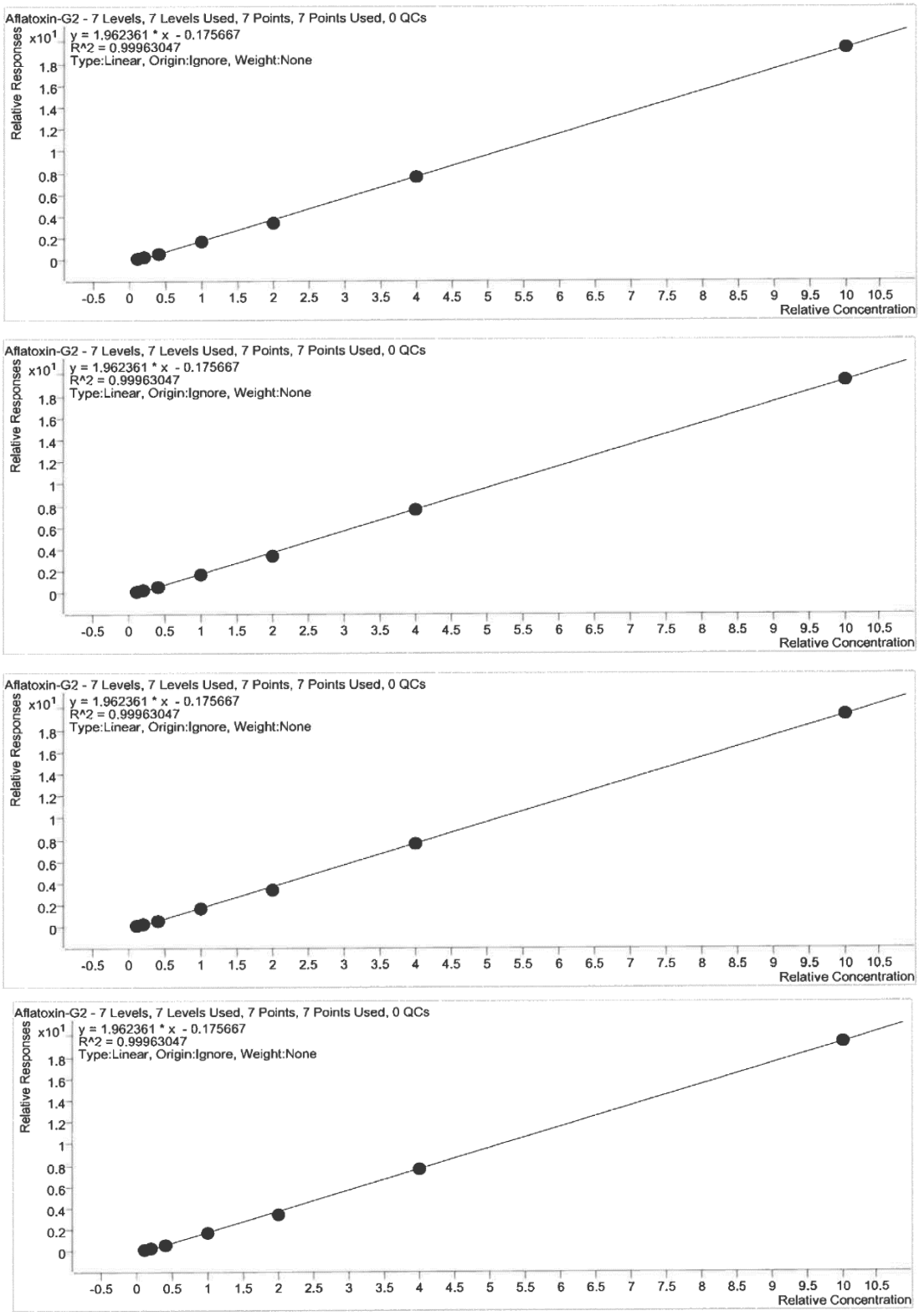


Figure 1. Calibration curves for aflatoxin (B1, B2, G1, G2) and ochratoxin A used for UHPLC–MS/MS quantification

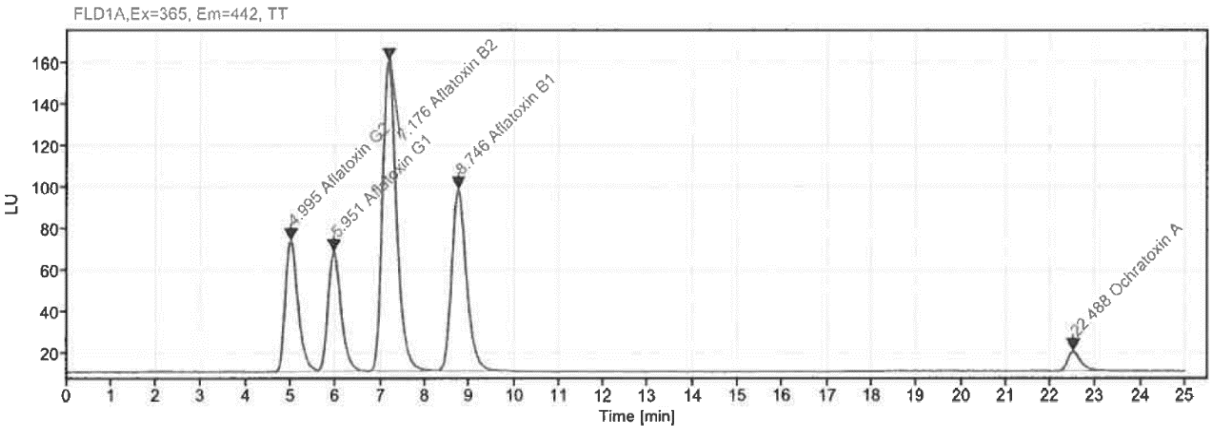


Figure 2. Calibration curve for Aflatoxin B1, B2, G1, G2 and Ochratoxin A standards

3.0 Results

3.1 Experimental Results

3.1.1 Environmental Condition

The environmental storage conditions for the purchased samples are presented in Figure 5, where the average room temperature was 19.4°C and the relative humidity (RH) was 63.6%. In addition, maximum temperatures of 24.0°C and 69.4% RH, and minimum temperatures of 19.0°C and 54.0 RH were observed, respectively.

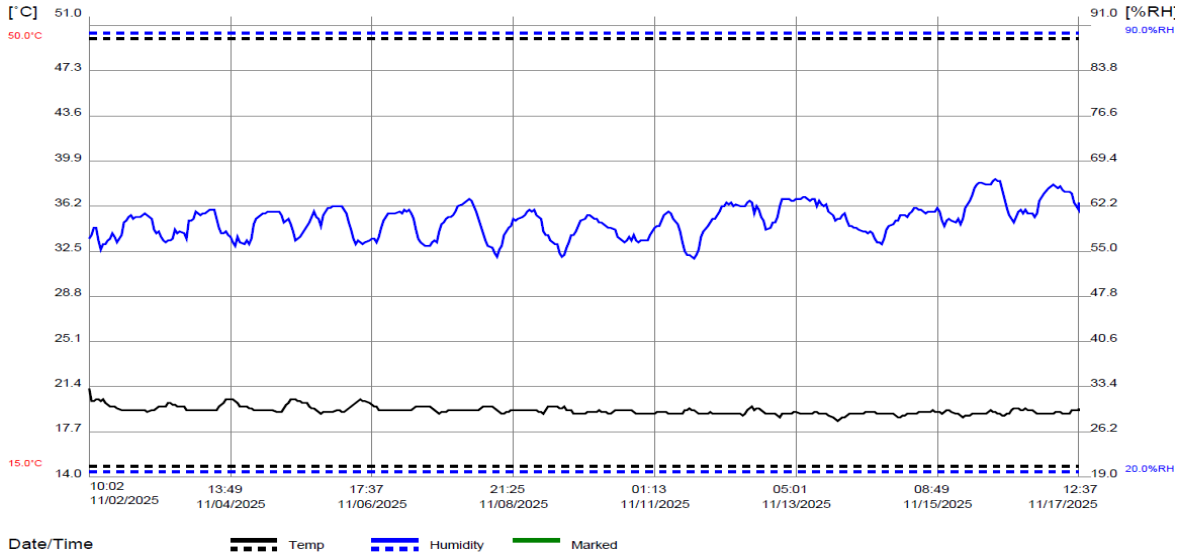


Figure 5. Evaluation of the storage room environmental condition

3.1.2 Fungal Isolation and Identification

Two media, Potato Dextrose Agar-PDA and Malt Extract Agar-Mea, used for the microbial assessment of the food sample revealed the presence of filamentous fungi, yeast, and bacteria in the samples. Both *Aspergillus* genera, *Penicillium, Cladosporium, Trichoderma, Mucor*, and yeasts, and unidentified genera were present in the various food samples analyzed right at the first week of sampling. Then, the light transmission microscope was used to reveal the morphological structure of individual filamentous fungi isolated from the food sample. Samples were later compared with online isolates for further identification. From the assessment - *Aspergillus Niger, Aspergillus Parasiticus, Aspergillus Flavus, Penicillium, and Cladosporium* (Figures 6 and 7).

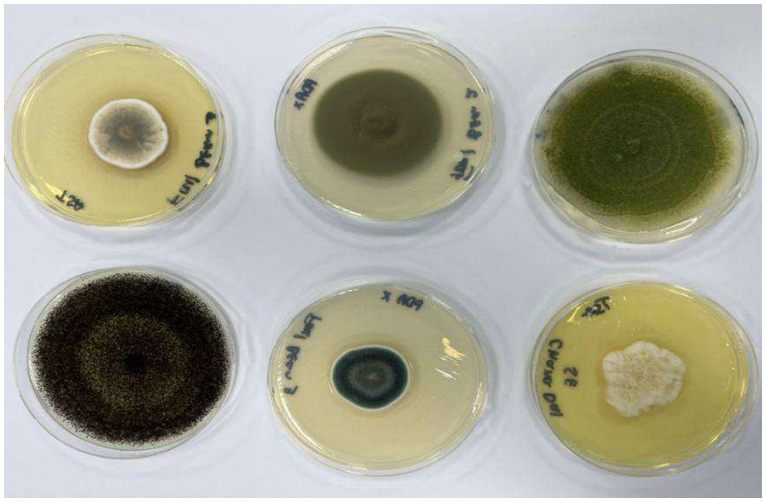


Figure 6. Fungi Colonies After 1 Week Growth on Potato Dextrose Agar (PDA) and Malt Extract Agar (MEA) Plate

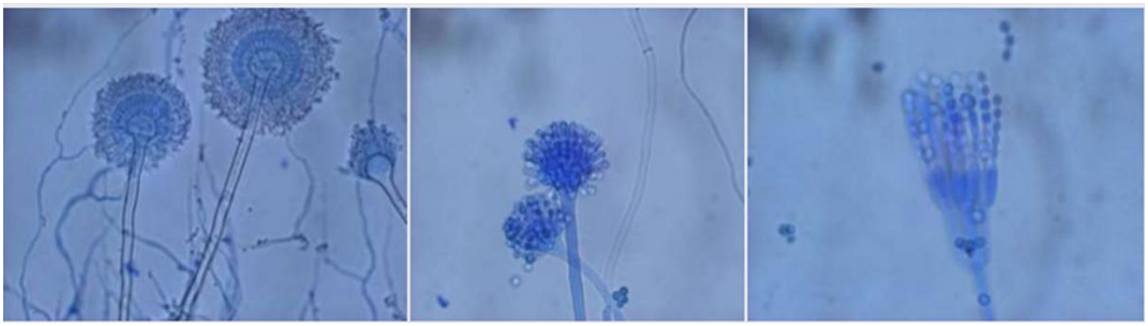


Figure 7. Fungal Isolates (*Aspergillus* and *Penicillium*) vViewed under Light Microscope

3.1.3 UHPLC–MS/MS Quantification

As shown in Table 4, total aflatoxins (AFT) and/or ochratoxins (OTA) were quantified in 11 out of the 41 samples (26.8%). In Batch 1, AFT was detected in moong dal (Green gram) at a concentration of 2.24 µg/kg, while OTA was detected in cashew nuts at 1.80 µg/kg. In Batch 2, AFT was detected in turmeric, soya chunks, and moong dal (Green gram) at concentrations of 0.61 µg/kg, 2.28 µg/kg,

and 2.28 μg/kg, respectively. OTA was also detected in turmeric at 0.37 μg/kg. Lastly, in Batch 3, AFT was detected in peanuts, rice (par-boiled), and turmeric with concentrations of 0.31 μg/kg, 2.08 μg/kg, and 0.20 μg/kg, respectively. OTA was detected in paprika and turmeric at concentrations of 0.39 μg/kg and 1.05 μg/kg, respectively. All detected levels of AFT and OTA were below the maximum limits determined by the European Union (EU) (European Food Safety Authority, 2024).

Table 4. High-performance liquid chromatography mycotoxin analysis results of 41 ready-to-eat dried farm products.

	Batch 1	AFT μg/kg	OTA μg/kg	Batch 2	AFT μg/kg	OTA μg/kg	Batch 3	AFT μg/kg	OTA μg/kg
1	White eye beans	ND	ND	Chickpea	ND	ND	Cashew	ND	ND
2	Fenugreek	ND	ND	Cummin	ND	ND	Almond	ND	ND
3	Foul Bean	ND	ND	Turmeric	**0.61**	**0.37**	Peanuts	**0.31**	ND
4	Moong dal (Green gram)	**2.24**	ND	Soya chunks	**2.28**	ND	Chia seeds	ND	ND
5	Sesame seeds roasted	ND	ND	Popcorn	ND	ND	Lentil	ND	ND
6	Cashew nuts	ND	**1.80**	Almond	ND	ND	Black pepper	ND	ND
7	Chickpea	ND	ND	Lentil	ND	ND	Paprika	ND	**0.39**
8	Mix Spices	ND	ND	Moong dal	**2.28**	ND	Kalonji Seed	ND	ND
9	Lentil	ND	ND	Black eye bean	ND	ND	Rice (par-boiled)	**2.08**	ND
10	Chana dal (chickpea)	ND	ND	Cardamon	ND	ND	Arabic coffee	ND	ND
11	Almond	ND	ND	Chana dal (chickpea)	ND	ND	Fenugreek	ND	ND
12	Black eye bean	ND	ND	Sesame seeds	ND	ND	Turmeric	**0.20**	**1.05**
13	Black Pepper	ND	ND	Black pepper	ND	ND	Chickpea	ND	ND
14				Sunflower seeds	ND	ND	Kalonji Seeds	ND	ND

Note: EU Limits for AFT in Nuts= 4 μg/kg; Legumes 4 μg/kg; OTA in cashew nuts: 3.0 μg/kg; paprika; 20 μg/kg. Turmeric 15 μg/kg

4.0 Discussion

This study provides important insights into the occurrence of mycotoxins in dried food products available in the State of Qatar, while highlighting the role of environmental conditions and fungal contamination in influencing food safety. The results indicate that mycotoxin contamination is present across a range of commonly consumed dry produce, although generally at levels below the maximum limits established by the European Union (EU). This is supported by evidence from the in-depth review that demonstrates a complex interaction between climate change and mycotoxin prevalence in

dry produce, with changing weather patterns playing a critical role in driving fungal growth and subsequent toxin production in staple crops such as maize, wheat, and sorghum (Kos et al, 2023; Battilani et al, 2016). These key findings are summarized in Table 4, which presents an integrated overview of environmental conditions, fungal contamination, and mycotoxin occurrence observed in this study.

Table 4: Data from Experimental Study in Qatar

Theme	**Key Findings**
Environmental Conditions	Average temperature: 19.4°C; RH: 63.6%
Fungal Contamination	Presence of *Aspergillus*, *Penicillium*, *Cladosporium*, and yeasts across multiple samples
Dominant Fungal Species	*Aspergillus* spp. widely detected across legumes, nuts, spices, and grains
UHPLC Results	9/41 samples (27%) tested positive for mycotoxins
Type of Mycotoxins	Aflatoxins and Ochratoxin A detected in multiple samples
High-Risk Food Item	Turmeric showed contamination with both AFT and OTA across batches
Batch Variability	Batch 3 had highest contamination; Batch 1 lowest
Regulatory Comparison	All detected levels below EU limits
Public Health Implication	Widespread low-level contamination across food types

The experimental assessment of dried produce samples collected from retail sources in Qatar revealed that the storage environment was characterized by average conditions of 19.4°C and 63.6% relative humidity. These conditions fall slightly below the optimal temperature range typically reported for mycotoxigenic fungal growth (20–30°C) (Yunes et al, 2019); however, fungal growth was still observed across multiple samples. This is consistent with the experimental findings of the present study, which identified genera such as Aspergillus and Penicillium, known for their mycotoxigenic potential, in a range of dried food products. This observation may be explained by evidence indicating that mycotoxin production does not always coincide with maximum fungal growth. For example, *Aspergillus nomius* has been shown to achieve peak growth at 30°C, while maximum aflatoxin production occurs at lower temperatures around 25°C, with higher temperatures potentially inhibiting toxin synthesis despite continued fungal proliferation (Yunes et al, 2019). Additionally, although temperatures below 10°C have been reported to suppress both fungal growth and mycotoxin formation (Wawrzyniak et al, 2024; Galván et al, 2024), the temperature range observed in this study (19–24°C) remains sufficient to support fungal activity.

The detection of low levels of aflatoxins and ochratoxin A in several samples further supports the role of these environmental conditions in facilitating both fungal growth and toxin production. This aligns with global evidence indicating that relative humidity plays a critical role in promoting fungal biomass

and mycotoxin accumulation, with higher humidity strongly linked to toxins such as deoxynivalenol (DON) and ochratoxin A (OTA) (Ortega et al., 2019; Lee et al., 2018). Climate-driven increases in humidity and rainfall variability have also been associated with elevated mycotoxin risks across different crops and regions (Kharbikar et al, 2015; Stanciu et al, 2019). In addition, the relationship between moisture and mycotoxin contamination is highly dependent on crop development stages and post-harvest conditions, where elevated humidity and inadequate drying can significantly increase toxin accumulation in grains and dried commodities (Kharbikar et al., 2016; Stanciu et al., 2019; Hassan et al., 2020). These findings emphasize the importance of effective moisture management not only during cultivation but also throughout storage and processing stages. Although drought conditions were not directly assessed in this study, existing evidence indicates that they can also contribute to mycotoxin contamination through indirect mechanisms. Drought stress may weaken plant defenses and increase susceptibility to fungal infection, often facilitated by insect damage that creates entry points for fungi (Martins et al, 2023; Cao et al, 2013). This highlights that mycotoxin risk is not limited to high-moisture environments but can also occur under dry, stress-induced conditions, particularly in arid regions. Collectively, these findings reinforce the complex, multifactorial nature of mycotoxin contamination and its sensitivity to environmental conditions and climate variability.

Evidence from crop-specific studies further demonstrates that mycotoxin contamination is influenced by both pre-harvest and post-harvest factors. In maize, drought stress promotes aflatoxin production by *Aspergillus* species, while humid conditions favor *Fusarium* infection and fumonisin accumulation. In addition, inadequate storage conditions, particularly elevated moisture, and temperature, significantly increase post-harvest contamination risks (Cao et al, 2013). Similarly, studies on wheat have shown that high humidity and rainfall during critical growth stages increase contamination with Fusarium mycotoxins, particularly deoxynivalenol (DON), with frequent co-occurrence of multiple toxins driven by shared environmental conditions (Ortega et al., 2019; Freitag et al., 2024b). These patterns are reflected in the findings of the present study. Microbiological analysis confirmed the widespread presence of fungal genera known for their mycotoxin-producing capabilities, particularly *Aspergillus* and *Penicillium*. The frequent detection of *Aspergillus* species, including *A. flavus*, *A. parasiticus*, and *A. niger*, is particularly relevant given their established role in aflatoxin production. These fungi were identified across multiple food categories, including legumes, nuts, and spices, indicating a broad contamination pattern across diverse commodities. The early appearance of these genera during incubation suggests that contamination may have originated prior to retail storage, potentially during production, processing, or transportation. This observation is consistent with findings reported across

multiple regions, where both pre-harvest environmental conditions and post-harvest storage practices contribute significantly to fungal colonization and toxin development, particularly in commodities such as maize and wheat (Cao et al, 2013).

Climate change projections further suggest that these commodities may become increasingly vulnerable as the number of favorable days for fungal growth increases under warmer, more humid conditions. Evidence from controlled storage studies supports this, demonstrating that conditions such as 25°C and 75% relative humidity can significantly increase DON accumulation, underscoring the importance of storage environments in driving post-harvest contamination (Zhang et al, 2019).

Quantitative analysis using UHPLC–MS/MS confirmed that 9 out of 41 samples (27%) contained detectable levels of mycotoxins. Aflatoxins were identified in multiple products, including moong dal, turmeric, peanuts, and rice, while ochratoxin A was detected in cashew nuts, paprika, and turmeric. Notably, turmeric was the only product consistently contaminated with both aflatoxins and ochratoxin A across different batches, suggesting a higher susceptibility of this commodity to multi-mycotoxin contamination. This is consistent with the microbiological findings of this study, which identified mycotoxigenic fungi such as *Aspergillus* and *Penicillium* across several samples. The co-occurrence of multiple mycotoxins has been widely reported in previous studies, particularly in cereals and dried commodities, where similar environmental conditions favor the growth of multiple fungal species simultaneously (Dalla Lana et al, 2021). Combined exposure to multiple mycotoxins may pose greater health risks than exposure to individual compounds alone.

Batch-wise variation in contamination levels was also observed, with Batch 3 showing the highest number of positive samples, while Batch 1 showed the lowest. This variability may reflect differences in sourcing, handling, storage conditions, or supply chain practices across retail types. Such variation is consistent with findings indicating that mycotoxin contamination is highly location-specific and influenced by microclimatic conditions, supply chain practices, and storage environments (Wawrzyniak et al., 2014; Yunes et al., 2019; Galván et al., 2021).

To better illustrate the interconnected pathways linking climate change, environmental conditions, fungal dynamics, and mycotoxin contamination, a conceptual framework is presented in Figure 10. This framework integrates the findings of the present study with existing literature, highlighting how climate-driven changes can influence fungal growth, crop susceptibility, and post-harvest conditions, ultimately contributing to mycotoxin occurrence and associated public health risks.

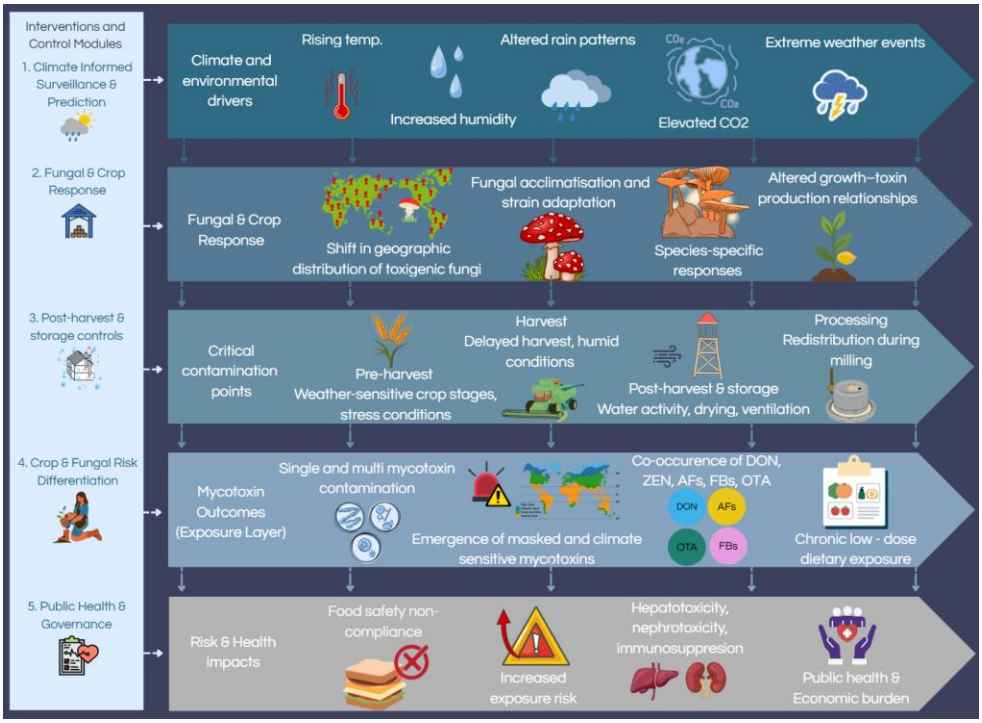


Figure 10: Conceptual framework illustrating the relationship between climate change, environmental drivers, fungal and crop responses, contamination pathways, and mycotoxin-related health risks.

5.0 Recommendations

Based on the findings of this study and supporting literature, several recommendations outlined in Figure 11 are proposed to reduce the risk of mycotoxin contamination in dried food products and enhance food safety under changing environmental conditions in arid regions like Qatar.



Figure 11: Climate-Adaptive Mycotoxin Risk Management Framework

Surveillance efforts should prioritize high-risk products, particularly spices (e.g., turmeric) and nuts, which are susceptible to contamination and co-occur with multiple mycotoxins (AFT and OTA). Targeted monitoring of these commodities, including cashew nuts, paprika, and mixed spices, can

enhance food safety and quality control. In addition, risk assessments should account for combined exposure to multiple mycotoxins rather than evaluating individual toxins in isolation.

The experimental findings demonstrated fungal presence as early as the first week of sampling, suggesting that contamination may originate prior to retail storage, likely during preharvest, processing, and or transportation stages. Therefore, monitoring efforts should extend across the entire supply chain rather than being limited to the point of sale. The use of environmental data loggers and routine laboratory testing can support early detection of contamination and enable timely interventions, particularly for high-risk commodities. Furthermore, notable variability was observed between batches, with higher contamination rates in samples from local shops and souqs (Batch 3) than in those from high-street retail outlets (Batch 1). This finding highlights the need for improved storage and handling practices, particularly in traditional market environments, through the implementation of consistent standards and enhanced monitoring measures.

Furthermore, maintaining appropriate storage conditions is essential to limit fungal growth and mycotoxin production throughout storage, transportation, and retail environments. In addition, reducing moisture levels and ensuring adequate ventilation can significantly minimize contamination risks in dried commodities such as spices, legumes, and nuts. Rigorous post-harvest drying, along with the use of moisture-proof packaging, is also critical to mitigate the effects of ambient humidity, which reached up to 69.4% in this study.

Another key point is that raising consumer awareness of proper household storage practices is important. Educating consumers on minimizing moisture exposure, maintaining proper storage conditions, and recognizing signs of spoilage can help reduce long-term exposure to mycotoxins. Finally, future studies should incorporate larger sample sizes, longitudinal monitoring, and real-time assessment of storage conditions across different stages of the supply chain. Integrating microbiological, chemical, and climatic data will provide a more comprehensive understanding of

contamination pathways, particularly in arid and semi-arid regions such as the Gulf, where context-specific evidence remains limited. Further research should also examine the combined effects of multiple mycotoxins and their potential health impacts under chronic exposure conditions. In addition, there is a need to develop climate-adaptive strategies, as changing environmental conditions may increase the number of days favorable for fungal growth and, consequently, the vulnerability of food products to contamination.

6.0 Conclusions

This study provides a comprehensive assessment of climate-driven mycotoxin contamination by integrating global evidence with experimental findings from an arid-region context. The in-depth review confirmed that temperature and humidity are the primary environmental drivers influencing fungal growth and toxin production, with clear regional and seasonal variability. Importantly, the experimental findings demonstrated that average storage conditions of 19.4°C and 63.6% relative humidity are sufficient to support fungal activity and mycotoxin biosynthesis. Although these conditions fall below the commonly cited optimal temperature range (20–30°C), they remain above the threshold required to inhibit contamination, indicating that standard room-temperature storage in arid environments does not necessarily eliminate risk. The analysis of 41 samples of grains, nuts, and spices revealed that 27% contained detectable levels of aflatoxins (AFT) or ochratoxin A (OTA). Reassuringly, all concentrations remained within European Union regulatory limits, reflecting alignment with internationally recognized food safety standards. However, the consistent detection of low-level contamination across multiple food products highlights the importance of considering cumulative dietary exposure. Notably, turmeric was identified as a particularly susceptible commodity, with consistent co-occurrence of AFT and OTA across batches, underscoring the importance of multi-mycotoxin assessment approaches. The findings further indicate that contamination is influenced by conditions throughout the entire supply chain rather than solely at the retail point.

Variability observed across sampling groups also highlights the influence of handling practices and localized environmental conditions, reinforcing the need for consistent quality control measures throughout the supply chain. By addressing a notable gap in the literature, this study contributes valuable evidence from an arid and semi-arid region, where mycotoxin research remains limited despite increasing climate-related risks. As climate change is expected to increase the frequency of conditions favorable to fungal growth, the findings underscore the importance of adopting adaptive, proactive food safety frameworks. Strengthening moisture and temperature management, enhancing surveillance of high-risk commodities, and integrating climate considerations into food safety systems will be essential to mitigate potential risks associated with cumulative exposure and multi-mycotoxin contamination. Overall, this study supports the development of resilient, climate-informed strategies to safeguard food quality and public health.

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