Journal of Food Composition and Analysis 146 (2025) 107991

Contents lists available at ScienceDirect

Journal of Food Composition and Analysis

journal homepage: www.elsevier.com/locate/jfca

Mycotoxins contamination of maize (*Zea mays* L) from different agroecological zones in Nigeria: A systematic review

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ARTICLE INFO

Keywords:
Public health
Intervention
Mycotoxins

ABSTRACT

Mycotoxin contamination in Nigerian maize was assessed across agroecological zones and seasons using data from 25 studies (1627 samples). aflatoxins (AFs) and ochratoxin A (OTA) showed 100 % occurrence in Sahel Savannah, while Fumonisins (FUMs) dominated Northern and Southern Guinea Savannah (87.5–93.8 %). Analytical methods included HPLC (29.6 %), ELISA (25.9 %), LC-MS/MS (25.9 %), and TLC (18.5 %). Rainy season exhibited peak contamination: total AFs (454.61 ± 66.62 μg/kg), FUMs (2267.20 ± 801.57 μg/kg), DON (407.96 ± 29.07 μg/kg), and ZEN (305.24 ± 63.56 μg/kg). Contamination ranges spanned 0–8422 μg/kg (AFs), 0–68,204 μg/kg (FUMs), 0–93.06 μg/kg (OTA), 0–18,800 μg/kg (DON), and 0–579 μg/kg (ZEN). Mean values exceeded EU limits in 27 % of rainy-season samples, with overall exceedances at 37.2 % (AFs), 32.6 % (FUMs), 22.95 % (DON), 22.8 % (OTA), and 3.13 % (ZEN). This review highlights critical mycotoxin risks in Nigeria's staple crop, urging immediate regulatory interventions and public health strategies to mitigate exposure. Seasonal and zonal variations emphasize the need for targeted monitoring in high-risk regions.

1. Introduction

Global maize production experienced significant growth from 313 million metric tons in 1971 to approximately 1162 million metric tons by 2020, reflecting an annual increase rate of about 3.06 % (Knoema, 2022). According to available data, global per capita maize consumption for food was around 18.5 kg annually, accounting for roughly 11 % of total cereal consumption excluding beverages (Knoema, 2022). In Africa, maize production reached about 87 million tons in 2018 (FAOStat, 2021). Nigeria's maize output was estimated at around 12 million metric tons in 2020, down slightly from the previous year's figure of approximately 12.7 million metric tons. This crop is crucial for household food security in Nigeria, contributing significantly to overall consumption patterns (Indexmundi, 2021). The Northern states of Nigeria particularly Kano, Kaduna, Bauchi, Gombe, Adamawa, Taraba, Jigawa have been among the top maize producing states in Nigeria with production increasing from 1977 to 2006 to 444.4 metric tons in 2006 (Knoema, 2022). However, fungi that produce mycotoxins can contaminate maize in the field, and during harvest, transportation, processing, and storage (Geary et al., 2016). The most commonly reported fungal pathogens colonizing corn and corn products include *Fusarium* spp., *Penicillium* spp., and *Aspergillus* spp. (Wu et al., 2014). They affect the quality and shelf life of food and beverages. Every year, food spoilage due to the growth of fungal diseases causes a huge loss in

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https://doi.org/10.1016/j.jfca.2025.107991
Received 17 April 2025; Received in revised form 27 June 2025; Accepted 3 July 2025
Available online 4 July 2025

world income (Faizan et al., 2019). Many fungi can produce mycotoxins such as aflatoxins, ochratoxin, fumonisins, zearalenone, and deoxynivalenol, making fungal spoilage a serious threat to food and safety (Milicevic et al., 2016). Throughout the food chain, mycotoxins can contaminate crops (Ezekiel et al., 2014) making them an international food safety and public health concern, with reports indicating that 25 % of maize and its products are differentially contaminated (Chilaka et al., 2017). They have different chemical structures and different toxicity levels and are stable in most food technologies (Temba et al., 2016). Mycotoxins can cause severe or chronic pain. Symptoms of poisoning include fever, vomiting, diarrhea, high blood pressure, and death (Ostry et al., 2017). Over time, mycotoxins have been associated with many diseases such as teratogenicity, carcinogenesis, immunotoxicity, malignancy, renal failure, growth retardation, and liver cirrhosis (Kimanya, 2015; Ostry et al., 2017). Mycotoxins are a significant contributor to cancer in Sub-Saharan Africa, ranking among the leading causes of cancer-related deaths in the region (Kimanya, 2015). The elderly, women, and children are particularly vulnerable to the adverse effects of mycotoxins due to their physiological susceptibility and dietary habits. Corn, is a primary ingredient in many of their diets, including porridge (Magoha et al., 2016). Therefore, there is a critical need to understand the prevalence, trends, and health impacts of mycotoxins over time, given maize's status as a staple food. Despite the availability of regional studies, comprehensive historical analyses are lacking, limiting the ability to assess long-term contamination patterns and the effectiveness of mitigation strategies. This review provides valuable insights on the prevalence of some selected mycotoxins on maize from different agroecological zones of Nigeria from 1993 till 2023, enabling policymakers to develop targeted interventions to ensure food safety and public health while supporting sustainable agricultural practices

2. Presentation of the different agroecological zones (AEZs) of Nigeria

The distribution and types of mycotoxins in maize in Nigeria vary across different agro-ecological zones due to climatic conditions, agronomic practices, and storage methods. Nigeria's geography is divided into several distinct agroecological zones, each characterized by unique climatic, soil, and topographical features that significantly influence the country's agricultural productivity. These zones can be broadly categorized as follows: Derived Savannah (DS): This zone is a transition area between the tropical rainforest and the Guinea savannah. It is characterized by scattered trees and tall grasses due to historical bush burning and cultivation practices. Southern Guinea Savannah (SGS): Part of the broader Guinea savannah zone, this area features a mix of trees and tall grasses. It extends across southern states like Ondo, Edo, Anambra, and Enugu. Northern Guinea Savannah (NGS): Also, part of the Guinea savannah zone but located further north with shorter grasses and fewer trees compared to its southern counterpart. While not explicitly listed in some classifications under "Mid Altitude," Nigeria does have high-altitude regions like Jos Plateau known for their cooler climate suitable for crops such as maize and wheat. However, "Mid Altitude" might refer to areas with specific elevation characteristics not widely recognized in standard agroecological zoning. Sudan Savannah (SS) is located more towards the north than other savannah zones with less rainfall than those further south. The vegetation here includes short grasses. Sahel Savannah (SHS) is situated at Nigeria's northernmost tip near Lake Chad, this zone experiences long dry seasons with sparse vegetation due to low rainfall levels below 700 mm annually. The Humid Forest (HF) or Tropical High Forest Zone is characterized by high rainfall levels supporting dense forest cover though much has been cleared over time for agriculture or urbanization. The DS area, spanning latitudes 6°8'–9°30' N and longitudes 2°40'–12°15' E, experiences binomial rainfall of 1300–1500 mm annually and temperatures between 25 and 35 °C. In contrast, the SGS region (latitudes 8°4'–11°3' N and longitudes 2°41'–13°33' E) receives less rainfall at around 1000–1300 mm per year with higher maximum temperatures ranging from 26 to 38 °C. The NGS (latitudes between approximately the same as SGS but slightly further north) has a unimodal rainfall pattern of about a thousand millimeters annually and even higher temperature ranges from about twenty-eight degrees Celsius up towards forty degrees Celsius. Further north lies the MA region with unimodal rainfall between one thousand and eighteen hundred millimeters annually alongside similar temperature ranges as DS (twenty-five to thirty-five degrees Celsius). Lastly, SS is characterized by significantly lower annual rainfall of six hundred fifty millimeters up towards one thousand millimeters across its latitudinal span near thirteen degrees north latitude; it also features notably low humidity except during brief periods when it rises above sixty percent primarily due to its extended dry season lasting nearly eight months on average (Adenle et al., 2020). The country experiences three main seasons: the Harmattan, the Dry season, and the Rainy (or Wet) season. The Harmattan season typically occurs from late November to February, characterized by dry, dusty winds from the Sahara Desert, by the Dry season from March to May, which is hot and sunny with little to no rainfall. The Rainy season then spans from June to October in the northern regions, while in the southern parts it starts earlier, around March or April, and lasts until October or November. Fig. 1 shows the different AEZs of Nigeria.

3. Methods

3.1. Search strategy

A comprehensive search was conducted using as the following search terms 'mycotoxins', 'maize', 'agroecological zones', and 'Nigeria' across various databases. This included the Nigerian National Scientific Databases, Universities thesis repositories, and global platforms like PubMed, Google Scholar, Scopus. The search spanned from 1993 to 2023 and focused on English-language articles. For manual Google searching, we used the names of the seven agroecological zones of Nigeria as well as the names of the States of the country. The aim was to gather relevant studies related to mycotoxin contamination in maize across different agroecological zones in Nigeria.

3.2. Eligibility criteria

To select relevant studies, specific criteria were applied. These included focusing on cross-sectional study designs and research conducted within Nigeria. Only articles published in English were considered. The studies had to report on the concentration of specific mycotoxins (Aflatoxins, Fumonisins, Ochratoxin A, Deoxynivalenol, and Zearalenone) in maize within Nigeria. Eligible articles were limited to original, published pieces with full text available. In addition, only studies that investigated unprocessed maize grain (from fields, storage facilities, or placed on the market for the final consumer) were included. Lastly, the publication period spanned from 1993 up to 2023. The exclusion criteria for the study included research focused on mycotoxins in products or foods other than maize, cases involving imports from other countries, articles examining food intended for animal consumption, and studies with restricted access to full-text or abstracts presented at scientific gatherings.

3.3. Study selection

The screening process involved evaluating articles based on their titles and abstracts, with those deemed irrelevant to the study being excluded. Subsequently, the full texts of the remaining articles were assessed to determine their relevance according to the eligibility criteria. To minimize selection bias, two authors independently reviewed the selected articles using these criteria. In cases where disagreements arose between the two reviewers, a third author was brought in to mediate and resolve the issue.

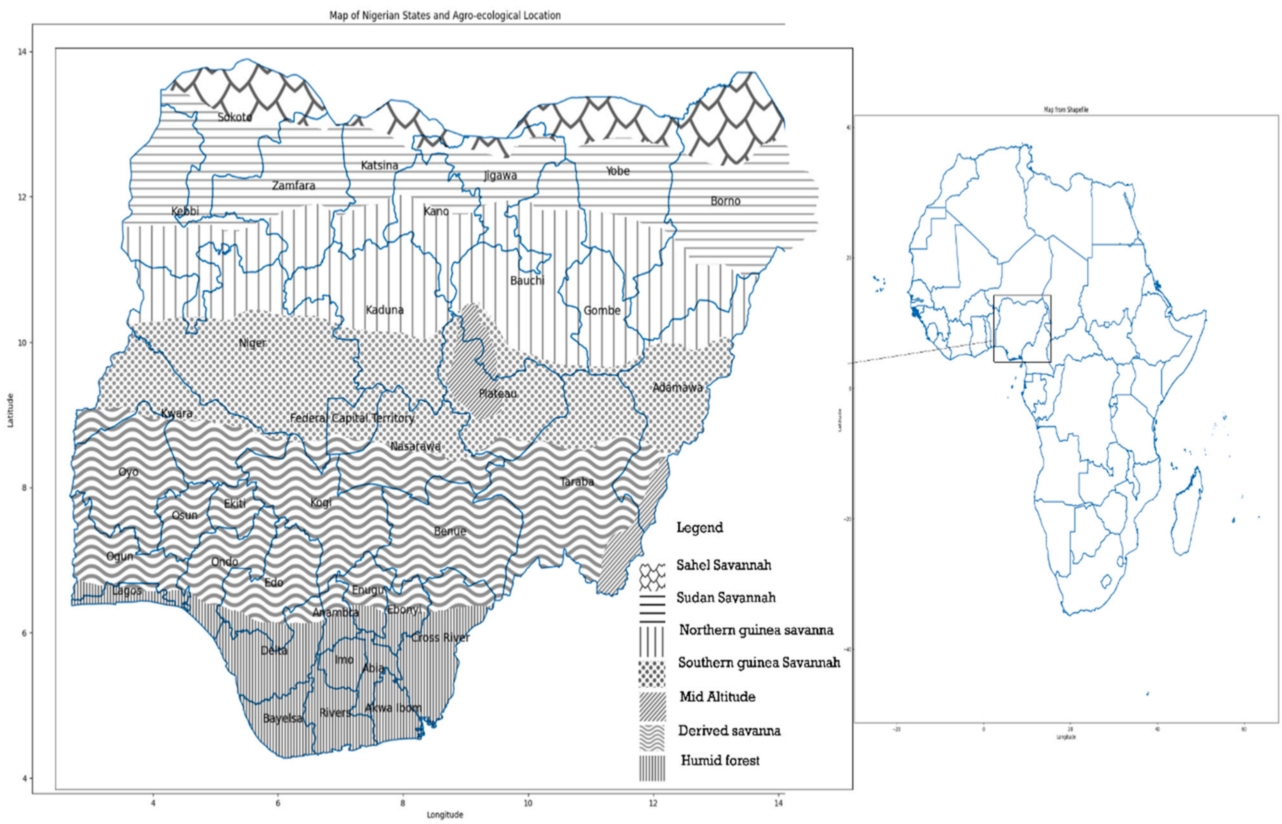

Fig. 1. Presentation of different agroecological zones of Nigeria.

3.4. Data extraction and reporting

The articles were thoroughly reviewed, and the necessary details were extracted for analysis. The information collected included the name of the first author, publication year, sample size, agroecological zones, sampling season, average contamination levels of each mycotoxin

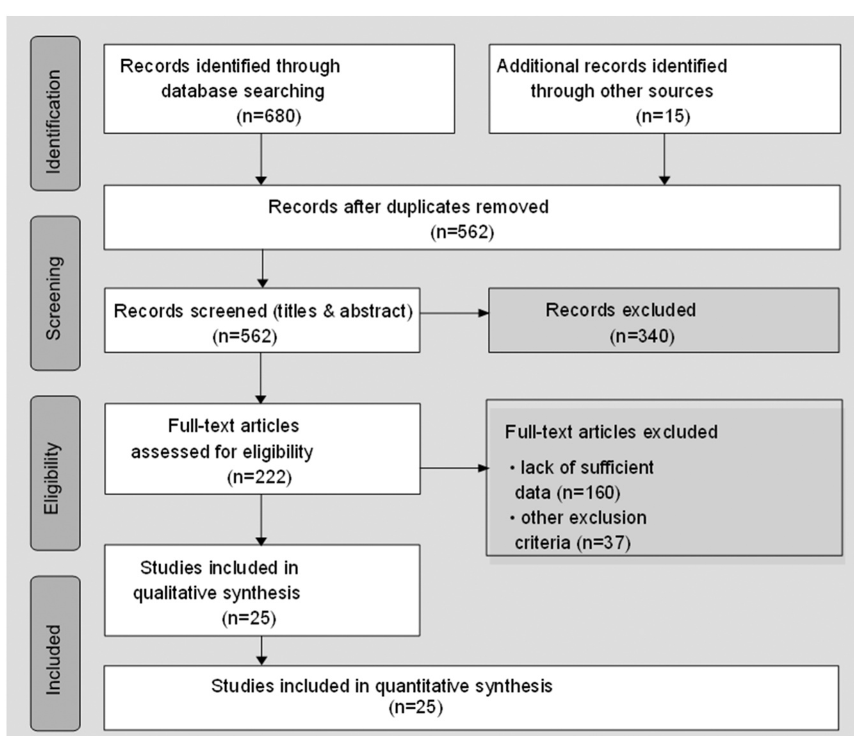

Fig. 2. The flow diagram of article selection in the current systematic review.

studied, instances of contamination exceeding European regulatory limits, the laboratory methods used to quantify mycotoxin levels, the limit of detection (LOD), The limit of quantification (LOQ) and the % recovery. The gathered data were organized and presented both in tabular form and descriptive text for clarity.

3.5. Data analysis

Data were processed and calculated using SPSS statistic version 23 to calculate the mean value and standard deviation of mycotoxins collected in each agroecological zone. It is important to note that the mean values were calculated exclusively from samples in which mycotoxin concentrations were detectable. Microsoft Office Excel Professional Plus 2016 (Redmond, WA, USA) for formatting and editing the tables.

4. Results

In the initial search phase, we retrieved a total of 695 articles. Following the removal of duplicates and irrelevant entries (473), we proceeded with evaluating the remaining pool for eligibility. This process involved excluding an additional set of articles due to irrelevance (222), ultimately leading to the selection of 25 pertinent studies published in English for our systematic review (Fig. 2). Key characteristics of these included studies are outlined in Table 1.

4.1. Characteristics of the included studies

Out of 25 examined studies, a total of 1627 samples (1478 single and 149 composites) were found. The occurrence of each agroecological zone in the different studies were NGS (20 %), SGS (17.5 %), DS (27.5 %), SS (10 %), SHS (2.5 %), HF (20 %), and MA (2.5 %). The analytical methods used in these 25 studies included Thin Layer Chromatography (TLC) (18.5 %), Liquid chromatography-tandem mass spectrometry (LC-MS/MS) (25.9 %), Enzyme-linked immunosorbent assay (ELISA) (25.9 %), High-Performance Liquid Chromatography (HPLC) (29.6 %). A total of 13 studies out of the 25 reported the season of sampling, harmattan season (29.4 %), dry season (17.6 %) and rainy season (53 %).

4.2. Mycotoxins contamination in maize in term of agroecological zones of Nigeria

4.2.1. Occurrence of mycotoxins in the zones

The incidence rate for each mycotoxin in the different agroecological zones is shown in Fig. 3. This figure shows that AFs and OTA has the highest occurrences in SHS (100 %). FUMs has the highest occurrence in NGS (87.5 %) and SGS (93.8 %). DON has the highest occurrence in SS (92.3 %).

4.2.2. Mycotoxins concentration in the zones

The concentrations of mycotoxins (AFs, FUMs, OTA, DON and ZEN) in maize from different agroecological zones of Nigeria are presented in Table 2.

4.2.2.1. Aflatoxins. A total number of 870 samples were analyzed for total aflatoxins in 16 studies in all the zones occurring in 67.01 % of the samples. The range of total aflatoxin contamination in all the zones was < 0.25–8422 μg/kg with a mean value of 340.05 ± 138.82 μg/kg (Table 2). The most contaminated agroecological zone was SHS, with a range of 200–300 μg/kg and a mean value of 1300 ± 919.23 μg/kg, followed by SGS with a mean 288.40 ± 25.39 μg/kg and range of < 0.4–2510 μg/kg, while the least contaminated zone for aflatoxin was HF, with a range of < 0.25–130 μg/kg and a mean value of 23.72 ± 3.4 μg/kg. When we look at the data chronologically, aflatoxins have shown fluctuating levels over the years, with notably high concentrations in 2012 (2350 μg/kg) in SHS and 2014 (335 μg/kg) (Table 1). These peak values suggest significant contamination events. There was also moderate presence in 1994 (200 μg/kg) in DS, and 2008 (120.12 μg/kg). Recent years like 2020 and 2021 show lower but still present levels (13.83–125.9 μg/kg), indicating ongoing but variable contamination. A general declining trend can be noticed after 2012, although sporadic spikes still occur (Table 1). Fig. 4 presents the different levels of aflatoxin contamination in various agroecological zones of Nigeria. From this figure, it is evident that all agroecological zones exhibit an average value exceeding the EU regulation limit of 10 μg/kg (European Commission (EC), 2023). The intensity of color increases progressively with the level of contamination across different zones. The white color symbolizes that no studies have been reported in that area.

4.2.2.2. Ochratoxin A. From the studies, 447 samples of maize samples were analyzed in 8 studies for OTA contamination in all the zones with 67.78 % occurrence. The overall contamination range was 0.02–93.06 μg/kg with the mean value of 20.32 ± 9.08 μg/kg (Table 2). The most contaminated agroecological zone was DS ranged from < 0.8–79 μg/kg with the mean value of 49.4 ± 28.52 μg/kg followed by SS ranging from < 0.8–21.03 μg/kg with the mean of 21.03 ± 0.00 μg/kg and SGS ranging from < 0.8–42 μg/kg with the mean of 20.38 ± 11.52 μg/kg. Ochratoxin A data is more sporadic over the years, with low values reported in most years. The highest value was seen in 2014 (135.45 μg/kg), followed by moderate concentrations in 2015 (14.28 μg/kg) in DS. In other years like 1994, 2012, and 2018, values were minimal (less than 1 μg/kg), suggesting limited contamination events. The latest value recoded in 2021 showed an increase value (26.2 μg/kg) in NGS and SGS (Table 1). Fig. 5 presents the level of contamination of OTA maize in Nigeria. The zone below the standard limit of 5 μg/kg according to the EU (European Commission (EC), 2023) is colored in green which represent the safety condition. The red color represents the zones with the mean values above the limit, and the intensity increases with the mean value. The zones without colors represent the zones without OTA data from the studies.

4.2.2.3. Fumonisins. From the 25 studies selected for this study, 771 samples were analyzed in 12 studies to detect the presence of FUMs occurring in 73.80 % samples. From all the agroecological zones, FUMs range from < 0.8 to 68,204 μg/kg with a mean value of 1330.05 ± 502.71 μg/kg (Table 2). The most contaminated agroecological zone was SGS with a range of < 0.8–6500 μg/kg and the mean value of 2171.6 ± 453.4 μg/kg followed by NGS having the range of 9.96–68204 μg/kg and the mean value of 1558.15 ± 899.60 μg/kg. There was not significance difference between DS (827.07 ± 337.65 μg/kg) and SS (827.12 ± 132.87 μg/kg) which represented the least contaminated agroecological zones. Fumonisins exhibit a wide range and increasing occurrence over time. In earlier years like 2004 and 2007, values were moderate (495 and 117 μg/kg in HF and DS respectively) (Table 1), but levels significantly increased in later years, 2153.16 μg/kg in HF in 2014, 783 μg/kg in DS in 2015, and an alarming value of 12,307 μg/kg in DS in 2019. Although 2020 and 2021 also showed high values (1317 and 2988 μg/kg in NGS and SGS respectively), the levels dropped slightly in 2023 (1280 μg/kg). These values reflect a growing concern regarding fumonisin contamination, particularly in the last decade. Fig. 6 presents the level of contamination of FUMs in all the zones. The zone below the standard limit of 1000 μg/kg according to the EU (European Commission (EC), 2023) is colored in green which represent the safety condition. The red color represents the zones with the mean values above the limit, and the intensity increases with the mean value. The white color represents the zones without FUMs values.

4.2.2.4. Deoxynivalenol. A total of 186 samples was analyzed in 6

Table 1
Specification of the selected studies.

Authors, year	Sample size	AEZS	Season of sampling	Mycotoxins analyzed	Positive samples (%)	Mean value (µg/kg)	LOD and LOQ (µg/kg)	% Recovery	Positive samples Above EU limit (%)	Laboratory techniques
Okoye (1993)	12	MA	Rainy season	DON	DON (25)	DON (2525)	Not reported	Not Reported	DON (25)	TLC
Adebajo et al. (1994)	50	DS	Not reported	Total AFs and OTA	AFs (45) OTA (5)	AFs (200), OTA (5)	Not reported	Not reported	AFs (45) OTA (0)	TLC
Bankole and Mabekoje (2004)	103	HF	Rainy season	Total AFs and FUMs	AFs (18.4), FUMs (78.6)	AFs (28), FUMs (495)	LOD (50)	Not reported	AFs (16.50), FUMs (5.8)	TLC and HPLC
Adejumo et al. (2007)	182	DS	Rainy season	ZEN and FUM	FB1(73), ZEN (57)	FB1 (117), ZEN (49)	LOQ (10)	Not reported	FB1 (0), ZEN (4.39)	LC-MS/MS
Atehnkeng et al. (2008)	55	DS, NGS, SGS	Not reported	Total AFs	Total AFs (52)	Total AFs (120.12)	Not reported	Not reported	AFs (100)	TLC
Obida et al. (2012)	6*	SHS	Rainy season	Total AFs and OTA	Total AFs (100), OTA (100)	Total AFs (2350), OTA (0.14)	Not reported	Not reported	AFs (100), OTA (0)	ELISA
Afolabi et al. (2013)	104	HF, DS, SGS	Not reported	ZEN	ZEN (37)	ZEN (52.5)	LOD (50)	88	ZEN (3.8)	ELISA
Adetunji et al. (2014)	70*	SS, NGS, SGS, DS, HF	Rainy season, Harmattan and Dry season	Total AFs, DON, Total FUMs, ZEN, OTA	Total AFs (68), DON (100), FUMs (92.9), OTA (10), ZEN (17.14)	Total AFs (335), Total FUMs (2153.16), DON (67.11), ZEN (36), and OTA (135.47)	LOD AFs (0.4–0.6), LOD DON (0.4), LOD FUMs (0.8–8), LOD OTA (0.8), LOD ZEN (0.3)	AFs (59.6–63.8), DON (96.8), FUMs (61.6–71.6), OTA (93.3), ZEN (81.5)	FUMs (80), DON (0), ZEN (2), OTA (8.6), AFs (57.1)	LC-MS/MS
Okeke et al. (2014)	9*	HF	Rainy season	Total AFs, FUMs	Total AFs (100), FUMs (100)	Total AFs (0.458), FUMs (2501.25)	LOD AFs (< 0.25)	AFs (70)	Total AFs (0), FUMs (37.5)	HPLC
Egbuta et al. (2015)	39	DS	Not reported	Total AFs, FUMs, DON, ZEN, OTA	AFs (94.9), FUMs (15.4), DON (69.2), ZEN (64.1), OTA (92.3)	Total AFs (10.24), Total FUMs (783), DON (0.3), ZEN (139.0), and OTA (14.8)	Not reported	Not reported	Not reported	HPLC
Anjorin et al. (2017)	30	NGS	Harmattan season	FB4 and AFG2	FB4 (96), AFG2 (6.7)	FB4 (765), AFG2 (22)	Not reported	Not reported	Not reported	LC-MS/MS
Ademola et al. (2018)	30	DS and HF	Not reported	Total AFs and Total FUMs	Not reported	FUMs (338.5), AFs (13.7)	LOD Afs (1.1–1.6), LOD FUMs (100)	Not reported	Not reported	LC-MS/MS
Neji et al. (2018)	20	HF	Not reported	AFB1, OTA, FUMs, ZEN	AFB1 (100), OTA (100), FUMs (100) ZEN (100)	AFB1(1.76), OTA (0.56), FUMs (139.46) ZEN (54.81)	Not reported	Not reported	AFB1 (0), OTA (0), FUMs (0) ZEN (0)	HPLC
Liverpool-Tasie et al. (2019)	71	DS	Harmattan and Dry Season	Total AFs and Total FUMs	AFs (51.7) FUMs (12.93)	AFs (42.7), FUMs (12,307)	Not reported	Not reported	AFs (87.5), FUMs (25)	LC-MS/MS
Akoma et al. (2019)	13	SS	Not reported	DON	DON (92.3)	DON (6.13)	LOD DON (0.01)	86.91	DON (61.53)	HPLC
Shehu et al. (2020)	93	SS	Not reported	Total AFs and FB1	AFs (85.7), FB1(42)	AFs (73.21), FB1 (2.03)	LOD AFs (0.18–0.21) LOQ AFs (0.33–0.42)	Not reported	Not reported	HPLC
Ayeni et al. (2020)	140	DS	Harmattan Season	Total AFs	AFs (99)	AFs (125.9)	Not reported	96.6 ± 9.41	AFs (88)	ELISA
Onyedum et al. (2020)	20	NGS, SGS	Not reported	Total AFS, FUMs and OTA	Total AFs (100), FUMs (75) and OTA (90)	Total AFs (13.83), FUMs (1317) and OTA (4.12)	LOD AFs (3), LOD FUMs (200), LOD OTA (1.9), LOQ AFs (9), LOQ FUMs (600), LOQ OTA (5.7)	AFs (85 ± 15), FUMs (80 %), OTA (90 ± 20 %)	Total AFs (95), FUMs (5) and OTA (20)	ELISA
Dabara (2021)	240	NGS and SGS	Not reported	OTA	OTA (89.1)	OTA (9.45)	LOD OTA (2)	70–100	OTA (89.06)	ELISA

(continued on next page)

Table 1 (*continued*)

Authors, year	Sample size	AEZS	Season of sampling	Mycotoxins analyzed	Positive samples (%)	Mean value (µg/kg)	LOD and LOQ (µg/kg)	% Recovery	Positive samples Above EU limit (%)	Laboratory techniques
Ezekiel et al. (2021)	142	NGS and SGS	Rainy and Dry season	Total AFs, Total FUMs, OTA, ZEN	AFs (66.2), FUMs (93), 0TA (3.5), ZEN (15.5)	AFs (99.4), FUM (2988), OTA (26.2), ZEN (2.01)	Not reported	Not reported	AFs (50), FUMs (43.7), OTA (41.5), ZEN (2.10)	LC-MS/MS
Ekpakpale et al. (2021)	12*	DS	Harmattan Season	Total AFs	AFs (100)	AFs (101)	LOD AFs (1.75)	85	AFs (8.3)	ELISA
Badmos (2021)	32*	NGS and SGS	Rainy season	DON, ZEN, FUM	DON (37.5), FUM (91), ZEN (21.9)	DON (24.9), FUM (1692.9), ZEN (26.31)	LOD FUM (200), LOQ FUM (250). LOD ZEN (20), LOQ ZEN (40)	DON (87.7), FUM (80), ZEN (70)	DON (0), FUM (71.81), ZEN (0)	FUM and ZEN (ELISA), DON (HPLC)
Olopade et al. (2021)	20*	HF	Not reported	DON, ZEN	DON (0), ZEN (75)	DON (0), ZEN (6)	LOD DON (2), LOQ DON (5), LOD ZEN (2), LOQ ZEN (6)	DON (84 ± 1.00), ZEN (104 ± 5.94)	DON (0), ZEN (0)	LC-MS/MS
Mabekoje et al. (2023)	124	NGS, SS, HF	Not reported	Total FUM (FB1 and FB2)	FUMs (94)	FUMs (1280)	LOD FUMs (20)	83 ± 5.6–88 ± 3.5	FUMs (2.41)	HPLC
Magomya and Mbatsav (2023)	10	DS	Rainy season	AFB1	AFB1 (100)	AFB1 (11.06)	Not reported	Not reported	AFB1 (90)	TLC

Abbreviations: Agroecological zones (AEZS), Limit of Detection (LOD), Limit of Quantification (LOQ), Percentage (%), Thin Layer Chromatography (TLC), Liquid chromatography-tandem mass spectrometry (LC-MS/MS), Enzyme-linked immunosorbent say (ELISA), High-Performance Liquid Chromatography (HPLC). AFs: aflatoxins, FUMs: Fumonisin, ZEN: Zearalenone, OTA: Ochratoxin A, DON: Deoxynivalenol, NGS: Northern Guinea Savannah, SGS: Southern Guinea Savannah, DS: Derived Savannah, HF: Humid Forest, SS: Sudan Savannah, SHS: Sahel Savannah, MA: Mid Altitude.

* Composite samples.

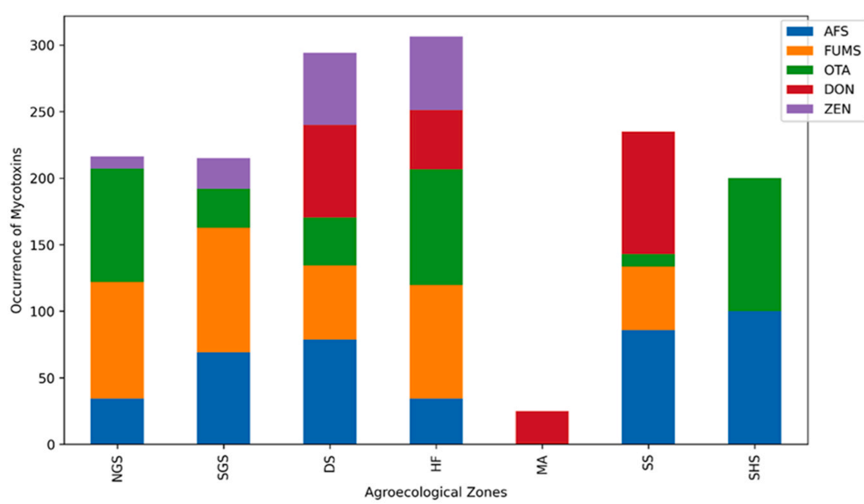

Fig. 3. Percentage of occurrence of mycotoxins in different agroecological zones of Nigeria (AF: aflatoxins, FUM: Fumonisin, ZEN: Zearalenone, OTA: Ochratoxin A, DON: Deoxynivalenol, NGS: Northern Guinea Savannah, SGS: Southern Guinea Savannah, DS: Derived Savannah, HF: Humid Forest, SS: Sudan Savannah, SHS: Sahel Savannah, MA: Mid Altitude).

studies for the detection of DON from the implemented studies occurring in 66.66 % samples. The range of DON contamination in all the zones varied from < 0.4 to 18,800 µg/kg with a mean value of 532.96 ± 238.47 µg/kg (Table 2). The most contaminated agroecological zone was MA the values ranged from < LOD to 18,800 µg/kg and the mean value of 2525 ± 0.00 µg/kg followed by NGS with the of < 0.4–173.325 µg/kg and the mean value of 67.07 ± 11.56 µg/kg. The least contaminated zone was DS with the range of 0.1–0.7 µg/kg and the mean value of 0.30 ± 0.00 µg/kg. Chronologically, DON data is intermittent but shows a moderate presence. In 1993, the level was very high (2525 µg/kg) in MA, and later values fluctuated 67.11 µg/kg in 2014, minimal amounts in 2015 (0.3 µg/kg) in DS, 6.13 µg/kg in 2019 in SS, and around 24.9 µg/kg in 2021 in NGS and SGS. Though the concentrations have generally decreased over time, the presence of DON continues to be detected, indicating a persistent but declining contamination trend (Table 1). Fig. 7 presents the level of contamination of DON on maize in the different agroecological zones of Nigeria. Colorless zones are zones without values from the selected studies. The green color represents the zone under the safety limit of 750 µg/kg according to the EU standard (European Commission (EC), 2023).

4.2.2.5. Zearalenone. Exactly 609 samples were analyzed in 6 studies for ZEN contamination on maize occurring in 37.60 % samples. ZEN ranged from < 0.3 to 579 µg/kg in all the zones with a general mean of

Table 2
Mycotoxins contamination in maize in terms of agroecological zones of Nigeria.

AEZ	Mycotoxins (μg/kg) AFs Range	AFs Mean ± SEM	OTA Range	OTA Mean ± SEM	FUMs Range	FUMs Mean ± SEM	DON Range	DON Mean ± SEM	ZEN Range	ZEN Mean ± SEM	Refs.
NGS	< 0.4–8422	135.84 ± 36.97	0.65–93.60	10.71 ± 6.18	9.96–68204	1558.15 ± 899.60	< 0.4–173.33	67.07 ± 38.72	< 0.3–154.74	10.08 ± 5.82	Atehnkeng et al. (2008), Anjorin et al. (2017), Onyedum et al. (2020), Dabara (2021), Ezekiel et al. (2021), Badmos (2021), Mabekoje et al. (2023)
SGS	< 0.4–2510	288.40 ± 25.39	< 0.8–42	20.38 ± 11.76	< 0.8–6500	2171.60 ± 453.40	< 0.4–200.13	42.06 ± 11.56	< 0.3–95	10.22 ± 5.11	Afolabi et al. (2013), Adetunji et al. (2014), Dabara (2021), Badmos (2021), Ezekiel et al. (2021), Onyedum et al. (2020), Atehnkeng et al. (2008)
DS	< 0.4–7380	155.02 ± 55.79	< 0.8–79	49.4 ± 28.52	10–14,620	827.07 ± 337.65	0.1–0.7	0.30 ± 0.00	< 0.3–579	75.66 ± 43.68	Adebajo et al. (1994), Magomya and Mbatsav (2023), Ekpakpale et al. (2021), Ayeni et al. (2020), Liverpool-Tasie et al. (2019), Adejumo et al. (2007),
SS	< 0.18–530	137.33 ± 0.00	< 0.8–21.03	21.03 ± 0.00	200–2080	827.12 ± 132.87	< 0.4–71.93	30.37 ± 21.47	< 0.3	36 ± 00	Adetunji et al. (2014), Mabekoje et al. (2023), Shehu et al. (2020), Akoma et al. (2019)
MA	_	_	_	_	_	_	<LOD-18,800	2525 ± 0.00	_	_	Okoye (1993)
HF	< 0.25–130	23.72 ± 3.46	< 0.8	_	53–3030	1266.31 ± 633.15	_	_	50–153	36.5 ± 0.00	Bankole and Mabekoje (2004), Afolabi et al. (2013), Adetunji et al. (2014), Okeke et al. (2014), Olopade et al. (2021), Ademola et al. (2018), Neji et al. (2018)
SHS	200–300	1300 ± 919.23	0.02–0.32	0.1 ± 0.00	_	_	_	_	_	_	, Obida et al. (2012)
Total	< 0.25–8422	340.05 ± 138.82	0.02–93.06	20.32 ± 9.08	< 0.8–68,204	1330.05 ± 502.71	< 0.4–18,800	532.96 ± 238.47	< 0.3–579	33.11 ± 19.11	

AEZ: Agroecological zones; SEM: standard error of mean.

33.11 ± 19.11 μg/kg. Globally, all the zones had the mean values below the EU standard of 350 μg/kg on maize. The agroecological zone having the higher mean value was DS (75.66 ± 43.68 μg/kg) followed by HF (36.5 ± 0.00 μg/kg). There was not significance difference between NGS (10.08 ± 5.82 μg/kg) and SGS (10.22 ± 5.11 μg/kg). ZEN was not reported in many years, but where reported, it shows considerable variation. Earlier values reported included 49 μg/kg in 2007 in DS, 36 μg/kg in 2014, and a spike in 2015 (139 μg/kg) in DS. More recent data from 2018 and 2021 show lower levels (54.81 μg/kg and as low as 2.01 μg/kg in HF and NGS respectively), suggesting a downward trend, though occasional increases still occur (Table 1). Fig. 8 below shows the level of contamination of ZEN in the different agroecological zones of Nigeria. From the figure, it is observed that the contaminated zones are colored in green because the mean values from the zones were below the EU standard of 350 μg/kg (European Commission (EC), 2023). The white color represents the zones without values.

4.3. Mycotoxins contamination in maize in terms of seasons

The occurrence of mycotoxins in maize is influenced by several factors, including seasonal variations. Table 3 shows the mean value of each mycotoxin for each season of sampling. It is observed that the rainy season has the highest mean values for total aflatoxins (454.61 ± 66.62), total fumonisins (2267.20 ± 801.57), Deoxynivalenol (407.96 ± 29.07), and Zearalenone (305.24 ± 63.56) compared to the dry and the harmattan seasons. Harmattan showed the lowest contamination for total aflatoxins (117.62 ± 107.70), total fumonisins (1532.72 ± 576.20) and the highest contamination for Ochratoxin A (135.47 ± 0.00). The dry season showed the lowest contamination for Zearalenone (19.00 ± 16.99) and deoxynivalenol (46.65 ± 20.45).

4.4. Mycotoxins contamination based on the standards of European Union (EU)

Fig. 9 below shows the graphical representation of the occurrence of mycotoxins contamination in the different agroecological zones of Nigeria based on the EU standards on maize. Total aflatoxins have the overall contamination rate of 37.2 % in all the zones with SHS having the high occurrence of 100 % followed by NGS (62 %). Fumonisins have the overall occurrence of 32.63 % in all the zones with SS having the highest occurrence of 67 % followed by SGS (40 %). Ochratoxin A has an overall contamination level of 22.8 % in all the zones with SGS (41 %) and SGS (34 %) having the highest occurrence. Deoxynivalenol has an overall contamination of 22.95 %. SS is the agroecological zone with the highest occurrence (41 %), MA and NGS have the same occurrence of 25 %. Zearalenone has an overall contamination occurrence of 3.13 %. The highest occurrence is found in DS (6 %).

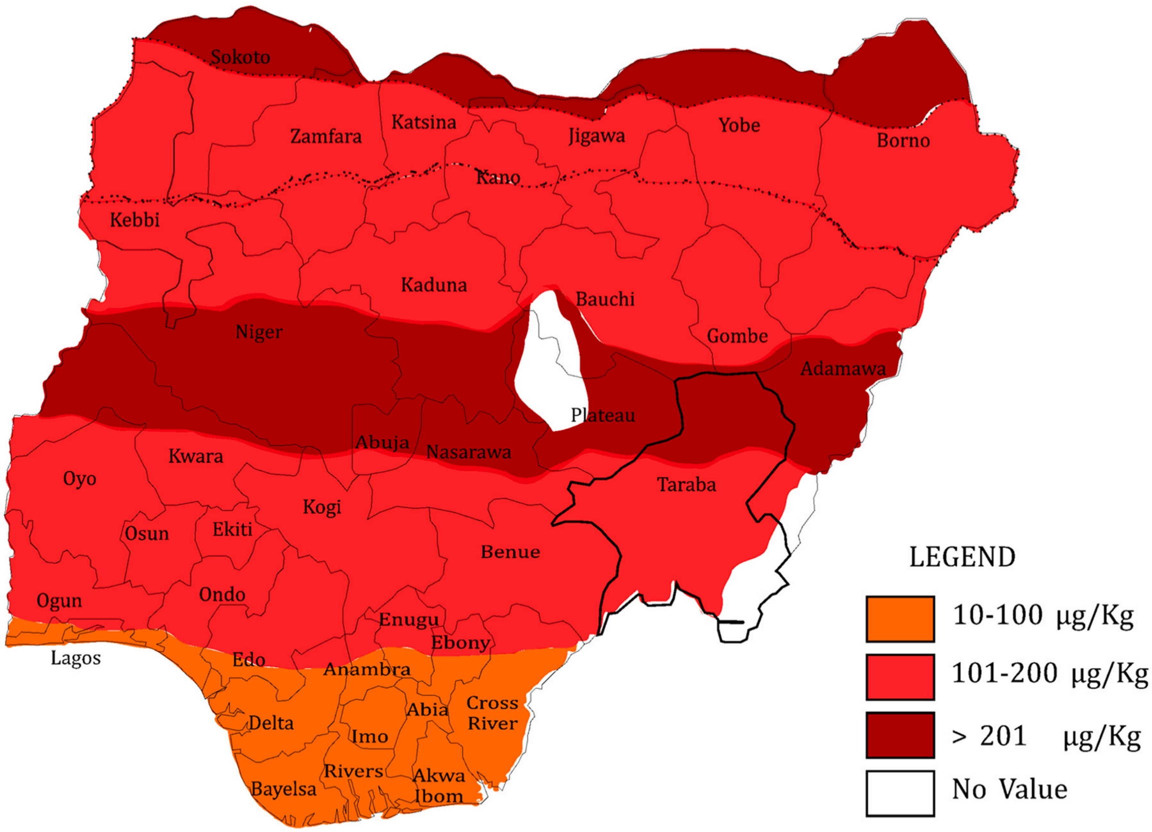

Fig. 4. Total mean of Aflatoxins contamination on maize in Nigeria.

4.5. Analytical instruments of the studies

The analysis of mycotoxins is crucial for ensuring food safety and compliance with regulatory standards. Various analytical instruments and methods have been developed for the detection and quantification of mycotoxins, each with its own advantages and limitations. The methods used on the implemented studies are Thin Layer Chromatography (TLC) (18.5 %), Liquid chromatography-tandem mass spectrometry (LC-MS/MS) (25.9 %), Enzyme-linked immunosorbent assay (ELISA) (25.9 %), High-Performance Liquid Chromatography (HPLC) (29.6 %). The graphical representation of each instrument from each agroecological zones is given on Fig. 10 below. TLC was the most used instrument in DS (42 %) to detect the different mycotoxins. ELISA was the most used instrument in SGS (30 %) and DS (30 %). HPLC was the most used instrument used in SS (27 %). LC-MS/MS was the most instrument used in DS (39 %).

5. Discussion

Maize is a staple food in Nigeria but it is prone to contamination by mycotoxins (Oyebamiji et al., 2023). This puts the population at risk of chronic exposure to these toxins through their diets (Abdurrazaq et al., 2022).

5.1. Geographical Variation

From the studies reviewed AFs and OTA had the highest occurrences in SHS (100 %). FUMs had the highest occurrence in NGS (87.5 %) and SGS (93.8 %). DON had the highest occurrence in SS (92.3 %) (Fig. 3). The high prevalence of aflatoxins, ochratoxin A (OTA), Fumonisin and Deoxynivalenol in maize within the savannah agroecological zones of Nigeria can be attributed to several interrelated factors: the Sahel region experiences a unique climate characterized by high temperatures and seasonal rainfall, which create optimal conditions for the growth of fungi such as *Aspergillus,* and *Fusarium* the primary producers of aflatoxins and fumonisins (Oyebamiji et al., 2023). These fungi thrive in warm, humid environments, especially during the rainy season when moisture levels are elevated (Talley et al., 2002). Poor agricultural practices, including inadequate crop rotation, improper harvesting methods, and insufficient post-harvest handling, contribute to increased fungal contamination. Maize is often left exposed to environmental stressors that promote fungal growth, leading to higher levels of mycotoxin production (Imade et al., 2021). Open-air storage methods expose maize to environmental conditions that favor mycotoxin development (Zheng et al., 2024). Studies indicate that maize stored in warehouses or poorly ventilated areas shows higher contamination rates than those stored under controlled conditions (Mugure et al., 2022). The transportation and marketing practices in Nigeria often exacerbate the problem. Maize is transported through unregulated channels where it may be subjected to further exposure to moisture and heat, increasing the likelihood of contamination (Mugure et al., 2022).). High levels of aflatoxins and OTA have been detected in maize consumed by vulnerable groups in Nigeria, including infants and children, leading to significant health risks (Adetunji et al., 2017). The simultaneous presence of multiple mycotoxins in maize increases the risk of adverse health effects. Studies have shown that aflatoxins and OTA frequently co-occur in maize samples from Nigeria, compounding the potential health impacts on consumers (Imade et al., 2021).

To safeguard the health of consumers and animals as well as the quality of food, mycotoxin concentrations in different products are regulated in several nations. Maximum concentrations of certain mycotoxins in various matrices have been defined by European legislation (European Commission (EC), 2023). Contamination of food and feed by mycotoxin-producing fungi continues to pose a threat to global food security, public health, and economic importance. To reduce the health risks associated with mycotoxin contamination, some countries have

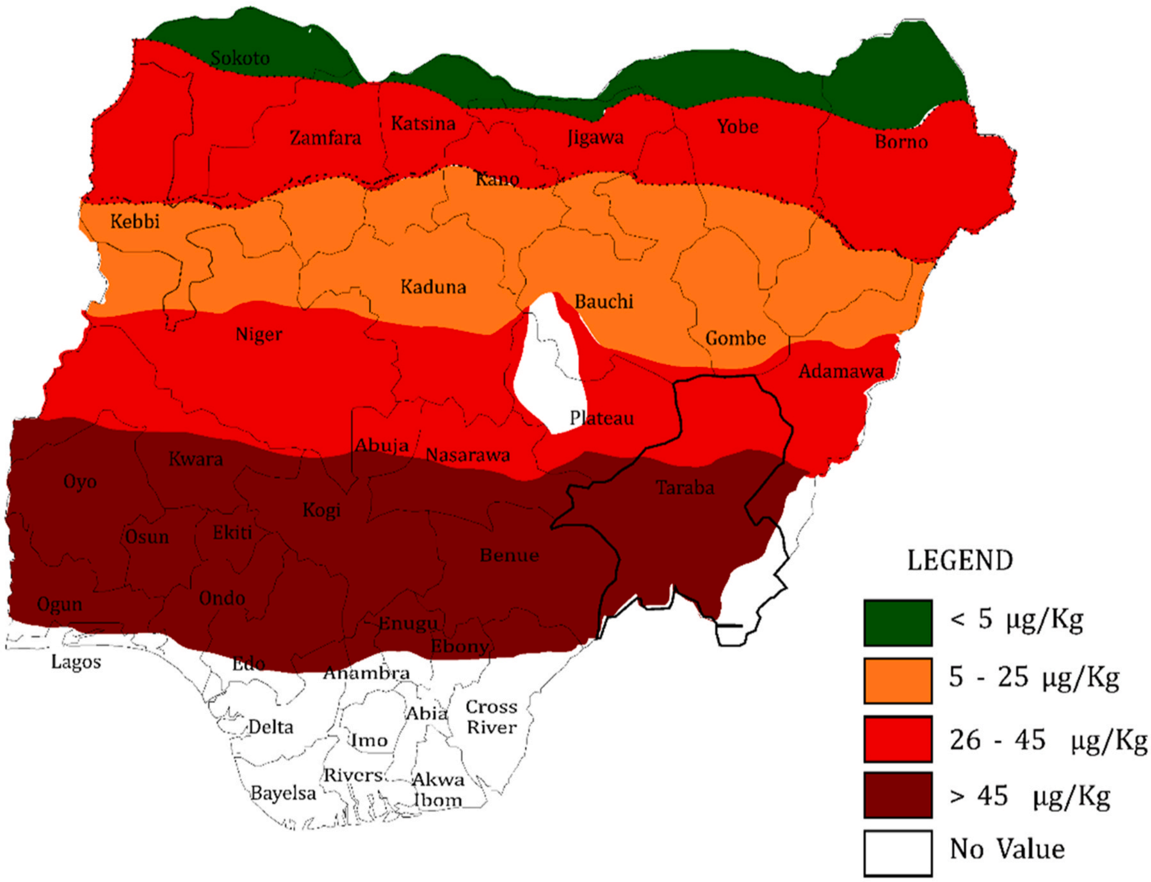

Fig. 5. Total mean of Ochratoxin A contamination on maize in Nigeria.

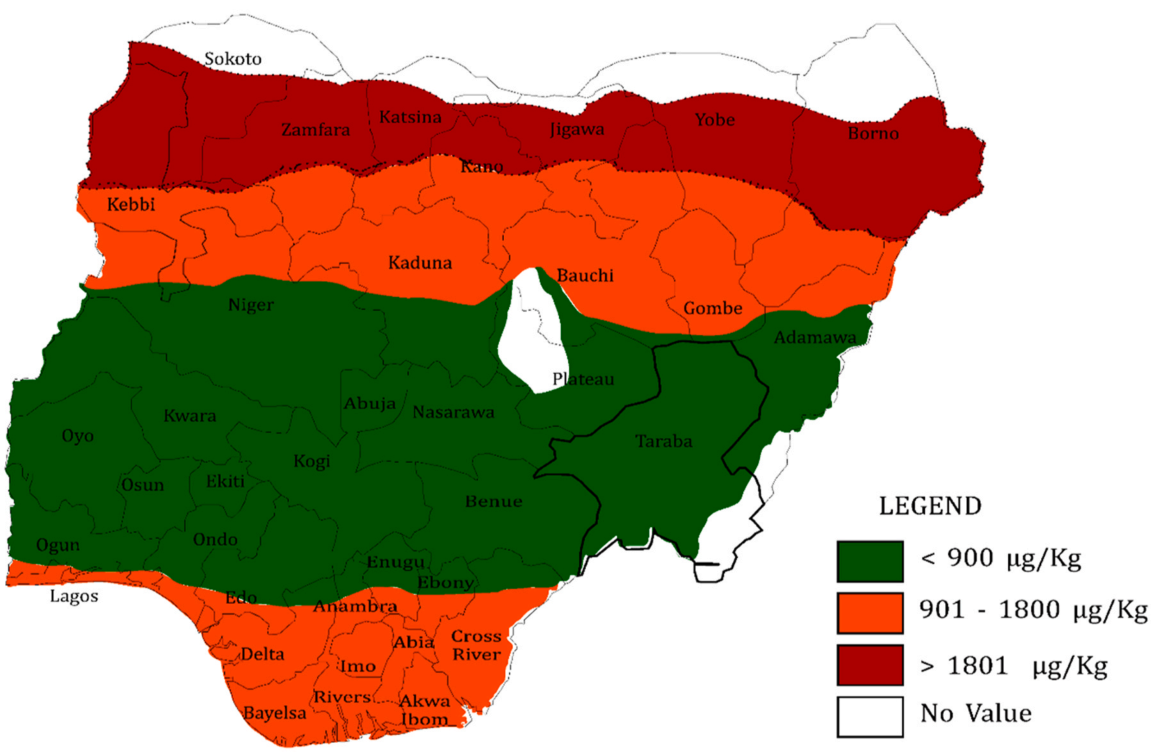

Fig. 6. Total mean of Fumonisin contamination on maize in Nigeria.

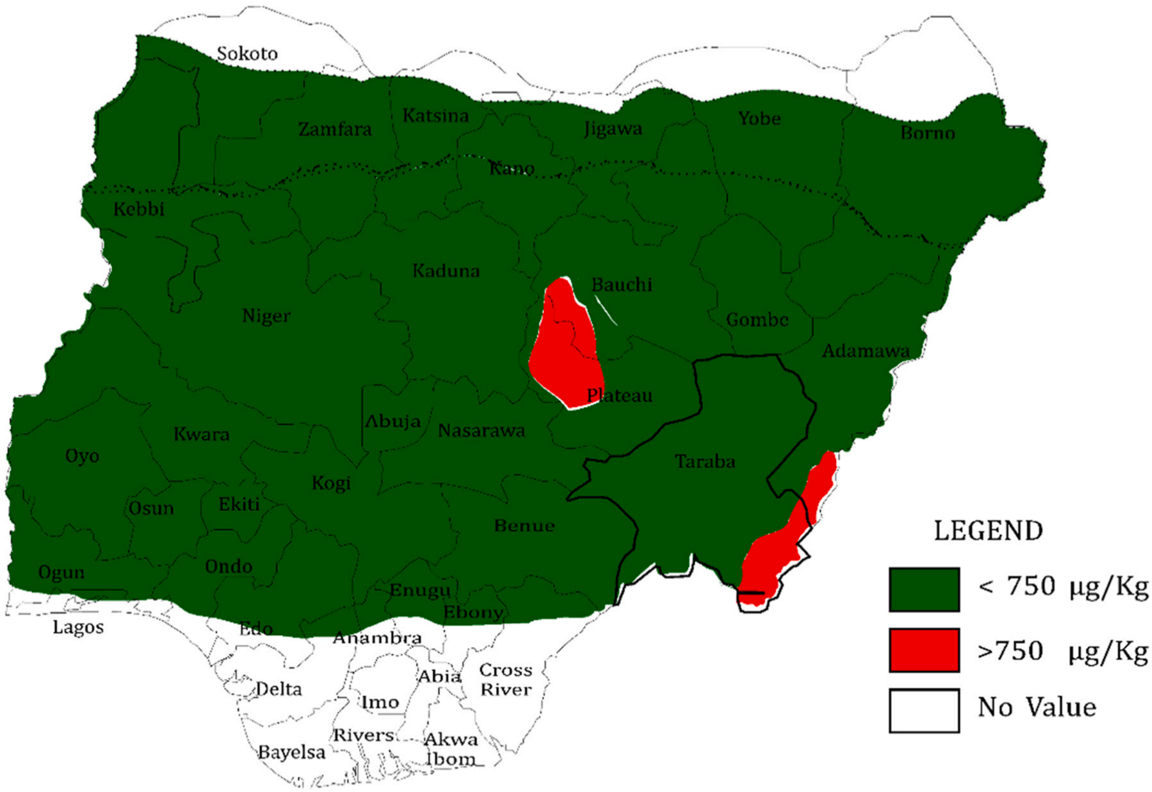

Fig. 7. Total mean of deoxynivalenol contamination on maize in Nigeria.

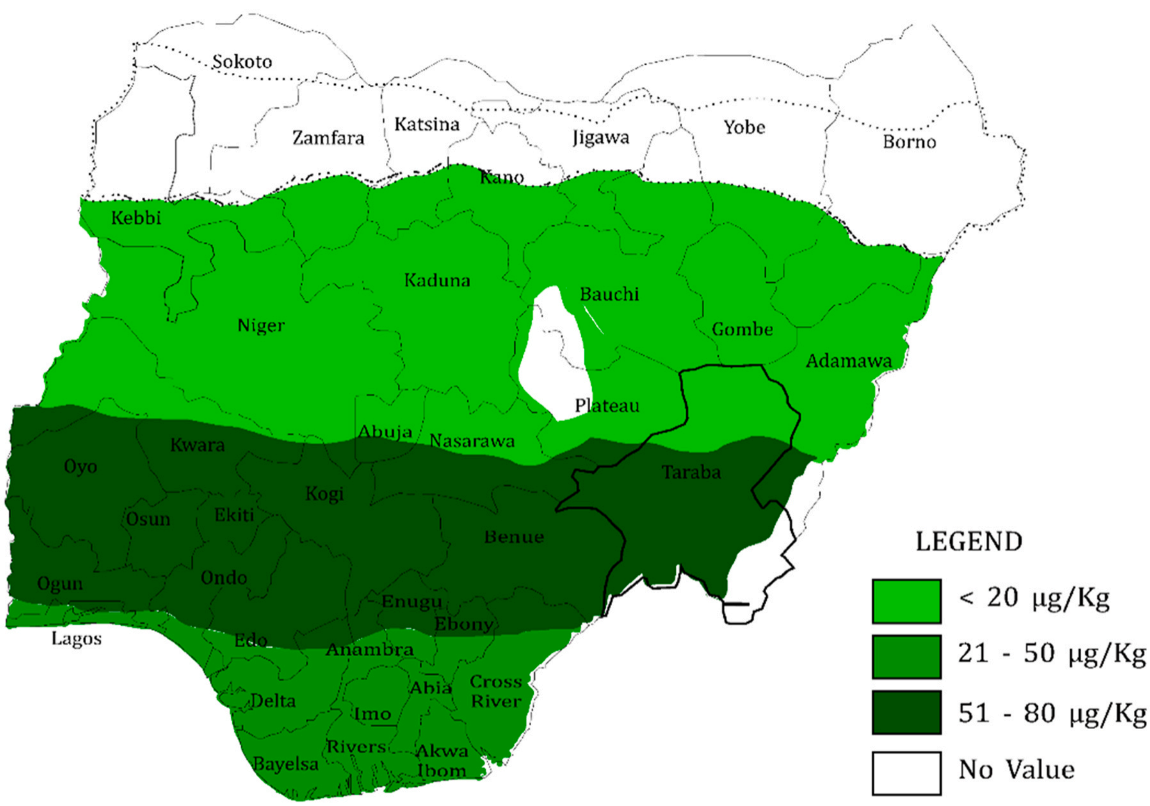

Fig. 8. Total mean of zearalenone contamination on maize in Nigeria.

Table 3
Mycotoxins contamination in maize in Nigeria in term of seasons.

Seasons of sampling	Mycotoxins (Mean ± SEM) μg/kg				
	AFs	OTA	FUMs	DON	ZEN
Rainy Seasons	454.61 ± 66.62	41.39 ± 12.89	2267.20 ± 801.57	407.96 ± 29.07	305.24 ± 63.56
Dry season	178.27 ± 89.13	54.55 ± 38.57	2122.04 ± 556.16	46.65 ± 20.45	19.00 ± 9.50
Harmattan season	117.62 ± 52.60	135.47 ± 0.00*	1532.72 ± 576.20	67.11 ± 0.00*	36 ± 0.00*

SEM: standard error of mean.
* Only one study reported the mean value for the analyzed mycotoxins.

placed limits on the amount of contamination that can be found in various foods and foodstuffs. Guaranteeing food safety, this also averts the growth of mycotoxins that cause health problems such as teratogenicity, hepatotoxicity, and cancer, as well as compromised immune systems, respiratory poisoning, and DNA structural damage (Akoma et al., 2019). The European Union has established strict regulations regarding the presence of mycotoxins in maize, particularly focusing on aflatoxins, fumonisins, deoxynivalenol, zearalenone, and ochratoxin A. Recently the EU regulations specified the following maximum levels for aflatoxins in unprocessed maize: Aflatoxin B_1: maximum limit of 5 μg/kg; total aflatoxins (B_1, B_2, G_1, G_2): maximum limit of 10 μg/kg; Ochratoxin A: maximum limit of 5 μg/kg; deoxynivalenol: maximum limit of 1750 μg/kg for the unprocessed maize and 750 μg/kg for the maize placed in the market for the final consumer; zearalenone: Maximum limit of 350 μg/kg for the unprocessed maize and 100 μg/kg for the maize placed in the market for the final consumer; fumonisin: maximum limit of 4000 μg/kg for the unprocessed maize and 1000 μg/kg for the maize place in the market for the final consumer (European Commission (EC), 2023). These regulations are crucial for ensuring food safety and protecting public health.

Total aflatoxins had the overall contamination rate of 37.2 % in all the zones based on the EU standard. One study reported that approximately 99 % of maize samples collected from markets in Ondo State were contaminated with total aflatoxins, with levels ranging from 0.65 to 265 μg/kg and an average of 125.9 μg/kg. Notably, 88 % surpassing the European Union's permissible limit of 4 μg/kg for total aflatoxins in food products (Ayeni et al., 2020). The consumption of contaminated maize poses serious health risks, including acute and chronic poisoning, which can lead to liver cancer and other health issues (Abdurrazaq et al., 2022). Despite the high levels of contamination, local regulations are often inadequate. 27 % of maize samples tested for all the mycotoxins were above the EU's acceptable limit, highlighting the need for improved monitoring and control measures (Olaitan et al., 2024). These findings underscore the urgent need for enhanced food safety measures and public awareness regarding aflatoxin risks associated with maize consumption in Nigeria.

5.2. Seasonal variation

The level of total aflatoxins, total fumonisins, Deoxynivalenol, and Zearalenone contamination in maize was found higher during the rainy season. In Nigeria, mycotoxin levels in maize are higher during the rainy

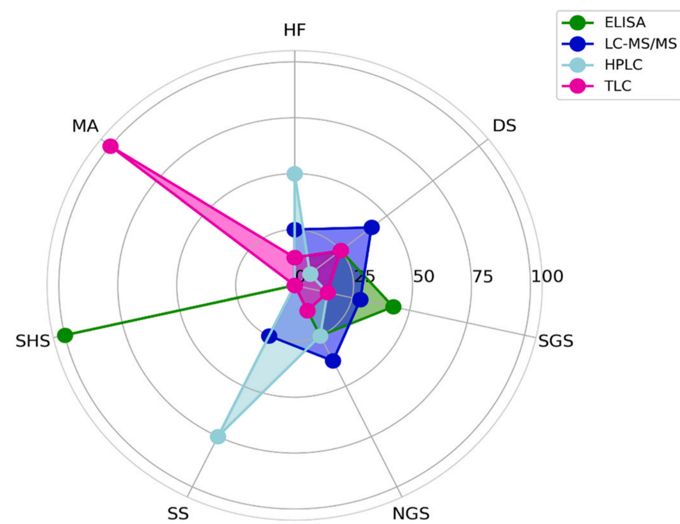

Fig. 10. Occurrence of analytical instrument used in the studies.

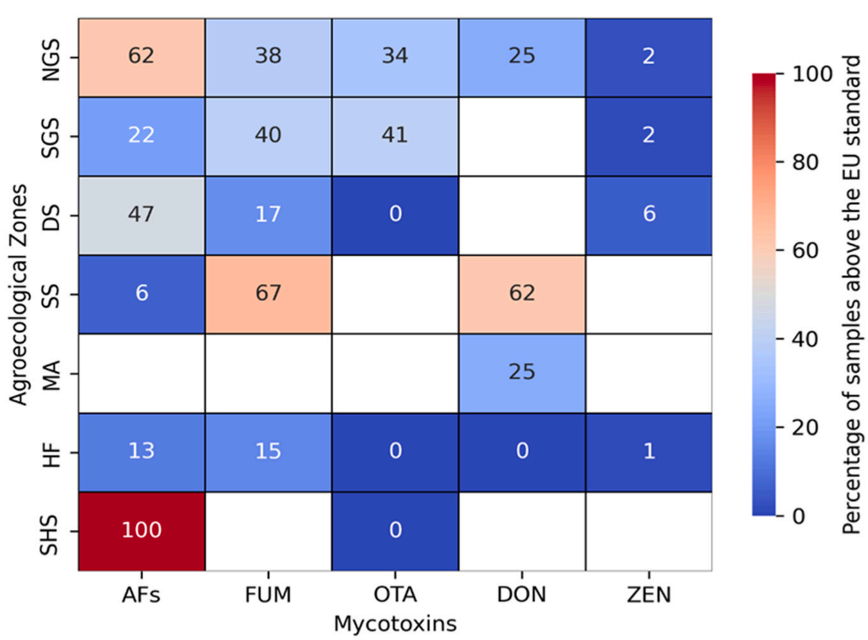

Fig. 9. Occurrence of mycotoxins contamination in maize based on the EU standard limit. Boxes without colors represent the zones where the number of analyzed samples above the limits were not reported.

season due to the combination of warm temperatures and increased humidity, which create ideal conditions for the growth of mycotoxigenic fungi such as *Aspergillus* and *Fusarium* species (Oyebamiji et al., 2023). These fungi thrive in moist environments, leading to elevated production of mycotoxins like aflatoxins and fumonisins. Studies have shown that regions with higher rainfall and humidity exhibit increased fungal contamination in cereals (Oyebamiji et al., 2023). For instance, research indicates that the Sudan Savanna and Northern Guinea Savanna zones, characterized by significant rainfall, have higher incidences of fumonisin contamination in maize compared to drier regions (Muhammad et al., 2019). Additionally, poor post-harvest handling and inadequate drying practices during the rainy season can further exacerbate fungal proliferation and mycotoxin production (Oyebamiji et al., 2023). Therefore, the climatic conditions prevalent during Nigeria's rainy season significantly contribute to heightened mycotoxin contamination in maize.

Harmattan showed the lowest contamination for total aflatoxins and total fumonisins. The Harmattan season, which occurs from December to March, is a dry period that can influence fungal and aflatoxin contamination in maize in Nigeria (Atehnkeng et al., 2022). While the search results do not explicitly state that the Harmattan season shows the lowest contamination of aflatoxins and fumonisins, one study indicates the lowest mean bacterial counts were recorded during the Harmattan season (Mu'azu et al., 2024). Additionally, low temperatures during the dry Harmattan period can result in low germination, which encourages pathogens (Binbol et al., 2006).

5.3. Analytical instruments

Various analytical techniques were employed to detect and quantify mycotoxins in maize, including High-Performance Liquid Chromatography (HPLC), Liquid Chromatography-Mass Spectrometry/Mass Spectrometry (LCMS/MS), Thin Layer Chromatography (TLC), and Enzyme-Linked Immunosorbent Assay (ELISA). This review critically evaluates these methods based on their applicability, sensitivity, specificity, and overall effectiveness in the context of mycotoxin analysis in Nigerian maize. Two of the most critical parameters in this context are the Limit of Detection (LOD) and Limit of Quantification (LOQ), which determine the smallest concentrations that can be reliably detected and quantified. Equally important is the percent recovery, which reflects the method's ability to extract and measure the actual mycotoxin content from a sample. Together, these parameters influence both the quality of analytical data and the risk assessment outcomes based on such data. HPLC is widely used for its high sensitivity and resolution in separating mycotoxins from complex matrices like maize. It allows for the simultaneous analysis of multiple mycotoxins, such as aflatoxins and fumonisins, which are commonly found in contaminated maize samples (Zheng et al., 2024). The need for extensive sample preparation can be time-consuming. HPLC requires expensive equipment and skilled personnel, which may limit its accessibility in resource-limited settings like Nigeria. HPLC methods provided intermediate sensitivity and acceptable recovery rates. Akoma et al. (2019) reported a notably low LOD of 0.01 μg/kg for DON and a recovery of 86.91 %, highlighting the method's competence in trace-level detection. Olopade et al. (2021) achieved LODs of 2 μg/kg for DON and ZEN with recoveries exceeding 100 % for ZEN, indicating high extraction efficiency but also the need to control overestimation due to matrix effects. The combination of moderate-to-low LODs and robust recovery positions HPLC as a reliable method for confirmatory testing, especially when LC-MS/MS is unavailable.

LCMS/MS offers superior sensitivity and specificity compared to HPLC alone, making it particularly effective for detecting low levels of mycotoxins (Zheng et al., 2024). It can provide structural information about the mycotoxins, aiding in the identification of unknown compounds. The complexity and cost of LCMS/MS systems can be prohibitive for many laboratories. Sample preparation is also a critical step that can introduce variability if not performed correctly. Studies using LC-MS/MS consistently demonstrated superior performance with respect to LOD, LOQ, and recovery rates. For instance, Adetunji et al. (2014) reported LODs ranging from 0.4 to 8 μg/kg for various toxins and corresponding high recoveries up to 96.8 % for DON and 93.3 % for OTA. These figures are within acceptable ranges defined by international standards such as the European Commission Regulation No. 2023/915 OF 25 April 2023 to achieve limits of quantification (LOQs) typically at or below 0.5 × the maximum levels, with preferred LOQs even lower (around 0.2 × ML) indicating that LC-MS/MS is capable of detecting low concentrations while ensuring the accuracy of the measured values. The dual advantage of high sensitivity and high recovery reinforces LC-MS/MS as a gold standard for multi-mycotoxin analysis, particularly in complex matrices like cereals where interfering substances are common.

TLC is a cost-effective method that does not require sophisticated instrumentation, making it accessible for many laboratories. It is relatively simple to perform and can provide quick results for screening purposes. TLC has lower sensitivity and resolution compared to HPLC and LCMS/MS, which may lead to false negatives or positives in mycotoxin detection (Okeke et al., 2014). It is generally not suitable for quantifying mycotoxin levels accurately. In the reported studies, TLC methods were generally less sensitive and lacked comprehensive reporting of recovery and quantification thresholds. For instance, Adebajo et al. (1994) and Magomya and Mbatsav (2023) did not report any LOD, LOQ, or recovery values. This lack of critical validation parameters raises concerns about the reliability of TLC results, particularly in samples with low-level contamination. Given that TLC is based on visual interpretation, it is prone to subjectivity, and the absence of quantification limits or recovery data compromises its suitability for regulatory or high-stakes applications.

ELISA is user-friendly and allows for high- throughput screening of samples, making it suitable for routine testing (Muhammad et al., 2019). It provides good sensitivity for specific mycotoxins and can be adapted for field use. The specificity of ELISA can be a limitation; cross-reactivity with similar compounds may occur. ELISA kits can be expensive, and the need for specific antibodies may limit their applicability to different mycotoxins present in maize (Oyeka et al., 2019). ELISA-based methods in these studies also showed promising LOD and recovery values, although they tend to have higher LODs than LC-MS/MS. For example, Onyedum et al. (2020) reported LODs of 3 μg/kg for aflatoxins, 200 μg/kg for fumonisins, and 1.9 μg/kg for OTA, with high recovery rates (85–90 %). Similarly, Dabara (2021) reported a wide recovery range (70–100 %) for OTA. While these results affirm ELISA's utility in surveillance and rapid screening, the relatively higher LODs especially for fumonisins could limit its application in detecting low-level contamination or in settings requiring high precision. Nonetheless, when used with proper calibration and validation, ELISA remains a cost-effective and reasonably sensitive method for routine monitoring.

The choice of analytical technique for mycotoxin analysis in maize largely depends on the specific requirements of sensitivity, specificity, cost, and available resources. While HPLC and LCMS/MS are preferred for their accuracy and reliability, TLC and ELISA offer practical alternatives for preliminary screening or resource-limited settings. Given the significant health risks associated with mycotoxin contamination in Nigeria, improving access to advanced analytical techniques remains crucial for food safety monitoring and public health protection. Further research into optimizing these methods could enhance their applicability in detecting mycotoxins effectively across different regions in Nigeria.

6. Conclusion

Mycotoxin contamination in maize poses a significant challenge in Nigeria, impacting both human health and the economy. This article presented the frequency of mycotoxin occurrence in maize in Nigeria.

Based on available research, it is clear that people and animals in the country are exposed to dangerous levels of mycotoxins over long periods, especially when eating maize. This study has shown that mycotoxin concentrations in maize samples (27 %) often exceed the limits set by European Union standards. Infants and young children are particularly vulnerable to the risks associated with mycotoxin exposure through maize consumption. The co-occurrence of multiple mycotoxins further exacerbates these health risks. FUMs and AFs appear to be the most prevalent and problematic over the years, with FUMs showing a rising trend in recent times. OTA, DON, and ZEA show more sporadic and generally lower concentrations, though certain years reveal significant spikes. The variability across years highlights the importance of continuous surveillance and mitigation strategies for mycotoxin contamination along the maize value chain, along with stricter tolerable limits, to address this persistent problem in Nigeria.

Author Statement

All authors have contributed significantly to the conception, research, and writing of this review and have read and approved the final version submitted. The authors are aware of this submission and have no conflict of interest. They have approved the version of the manuscript and consented to its submission. The authors confirm that neither the manuscript nor any parts of its content are currently under consideration or published in another journal.

The authors have carefully addressed all the reviewers' comment and suggestion, improving the manuscript accordingly. A detailed response of the comment has been provided separately.

CRediT authorship contribution statement

Edzili Awono Antoine Thierry: Writing – original draft. **Ossamulu Ifeanyi:** Writing – review & editing. **Isa Abdullahi Bala:** Writing – review & editing. **Dogo Eustace:** Supervision. **Hadiza Kudu Muhammad:** Validation. **Auta Helen Shnada:** Visualization. **Susan Bekosai Salubuyi:** Writing – review & editing. **Jesse Polly Shingu:** Visualization. **Hadiza Lami Muhammad:** Project administration. **Essia Ngang Jean Justin:** Supervision. **Hussaini Anthony Makun:** Supervision, Funding acquisition.

Funding details

This work was supported by the Tertiary Education Trust Fund, National Research Fund (TETFUND NRF), Federal Republic of Nigeria, Grant no.: TETF/ES/DR&D CE/NRF2021/SETI/AFS/00335/01VOL.1.

Declaration of Competing 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.

Acknowledgements

We would like to express our sincere gratitude to Emmanuel Augustin for his exceptional graphic design work, which significantly enhanced the visual presentation of this manuscript. His expertise and creativity were invaluable in crafting the graphs and illustrations that support our findings. Additionally, we extend our heartfelt thanks to Joseph Kumphanda for his meticulous editorial assistance. His dedication to refining the language, structure, and overall coherence of the manuscript has greatly improved its quality and readability. Their contributions were instrumental in bringing this work to fruition, and we are deeply appreciative of their efforts.

Data availability

Data will be made available on request.

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