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Co-occurrence of mycotoxins contamination and risk assessment of dietary intake in maize (*Zea mays* L) from Nigeria

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ABSTRACT

The study assessed prevalence, co-occurrence and dietary risk of aflatoxins (AFs), ochratoxin A (OTA), zearalenone (ZEA) and deoxynivalenol (DON) in 90 composite maize samples from farms, stores and markets across Nigerian agro-ecological zones (AEZ) using Ultra High Performance Liquid Chromatography (UHPLC) with immunoaffinity cleanup. 92.2% of samples were contaminated with total AFs (mean 39.58 ± 6.40 μg/kg; max 356.16 μg/kg). These exceeded European Union (EU; 10 μg/kg) and National Agency for Food and Drug Administration and Control (NAFDAC; 20 μg/kg) limits in 56.7% and 46.7% of samples, respectively with the highest mean level in Southern Guinea Savanna (SGS; 79.40 μg/kg). OTA occurred in 52.2% (mean 4.51 ± 1.02 μg/kg; max 48.75 μg/kg), with highest means in Sahel and Sudan Savannas (11.85 and 11.76 μg/kg). ZEA was restricted to Humid Forest (HF; 66.7% positive; mean 238.88 ± 86.53 μg/kg; max 897.02 μg/kg), while DON was found in 13.3% of samples (mean 8.28 ± 3.31 μg/kg; max 157.36 μg/kg) with the highest mean in Sahel (31.02 μg/kg). The samples from markets and stores were more contaminated than samples from farms. Infants faced the greatest risk: aflatoxin MOE <1 in SGS (0.61; 11.86 liver cancer cases/100 000/year), OTA %TDI at 243 970% (Sahel), ZEA at 836 080% (HF), and DON at 10 857% (Sahel). National infant AFs exposure (138.5 ng kg^{-1} bw·day^{-1}), compounded by hepatitis B, indicates a public health emergency requiring urgent, AEZ-specific regulatory interventions.

1. Introduction

Maize (*Zea mays* L.) is one of the most vital staple crops globally and provides a primary source of food and animal feed, particularly in Nigeria where it plays a crucial role in food security and the economy. In 2025, Nigeria's maize production was estimated at about 11.9–13.4 million metric tons, up slightly from around 11.2 million metric tons in 2024 (NAERLS, 2025). In Nigeria, this crop is essential for household food stability and greatly influences general consumption trends (Index mundi, 2021). Approximately 80 percent of the produced maize is consumed by humans and animals, and the remaining 20 percent is processed industrially into assorted products (Thierry et al., 2025). Maize contributes about 10% of the daily calorie intake in the country, with an average per capita consumption of approximately 35 kg per year (Thierry et al., 2025).

However, maize is highly susceptible to contamination by various mycotoxins, which are toxic secondary metabolites produced by fungi such as *Fusarium*, *Aspergillus*, and *Penicillium* species. These mycotoxins often occur simultaneously in maize, leading to co-occurrence that can exacerbate health risks. Globally, aflatoxin exposure is estimated to contribute to 25 200–155 000 liver cancer cases per year, representing about 4.6–28.2% of all hepatocellular carcinoma cases, with a substantial share occurring in sub-Saharan Africa (Liu et al., 2012). Fumonisins are associated with elevated human esophageal cancer while ochratoxins are known to cause liver and kidney impairment in man and animals (Sokefun et al., 2018). Mycotoxins account for 25 %

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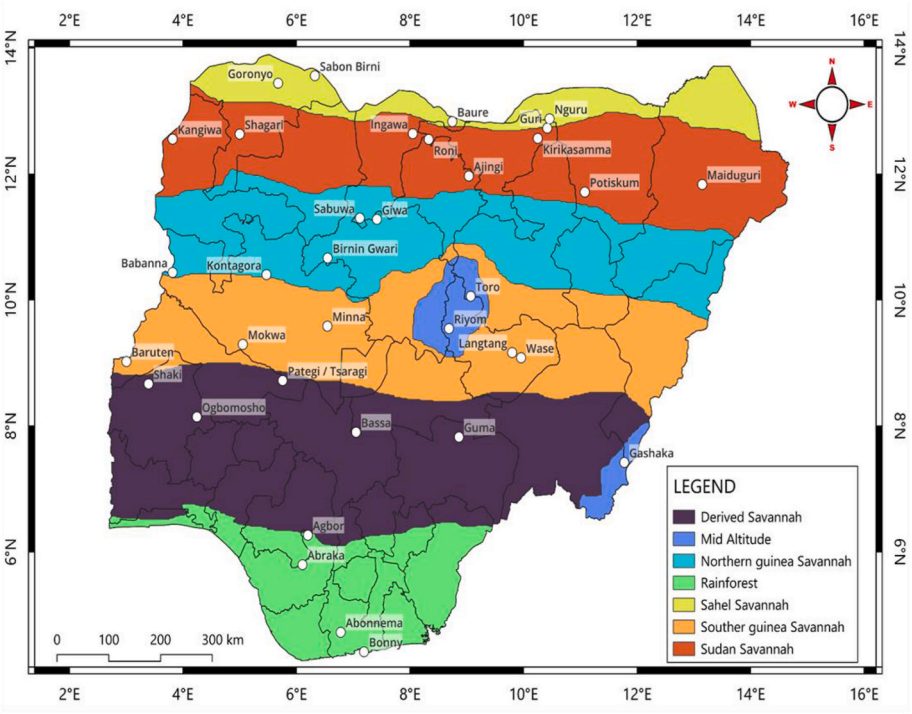

Fig. 1. Overview of the agro-ecological zones with sampling sites of Nigeria.

Table 1
Geographic coordinates and weather conditions of the sampling sites in the seven agroecological zones (AEZs) of Nigeria.

AEZs	State	District	N sample Collected	N Composites	Latitude	Longitude	Altitude	Rainfall Range (mm^3)	Average temperature range (°C)
MA	Plateau	Wase	9	3	9.094° N-9.62° N	8.77° E −9.956° E	247 m	1300-1500 1300-1500	25-35
	Plateau	Riyom	9	3	9.094° N-9.62° N	8.77° E −9.956° E	1070- 1210 m	1300-1500	25-35
	Plateau	Lantang	9	3	9.094° N-9.62° N	8.77° E −9.956° E	543 m	1300-1500	25-35
	Bauchi	Toro	9	3	10.44° N	9.22° E	984 m	1300-1500	25-35
DS	Kogi	Bassa	9	3	7.900°N,	7.050°E	190 m	1000-1800	23-35
	Oyo	Ogbomosho	9	3	8.13° N	4.13° E	347 -352 m	1000-1800	23-35
	Benue	Guma	9	3	7°32′N- 8°51′N	9°22′E – 9°35′E	131 m	1000-1800	23-35
	Taraba	Gashaka	9	3	7° 00′ N - 10° 00′ N	7° 30′ E– 8° 45′ E	666 m	1000-1800	23-35
	Kwara	Pategi	9	3	8.73° N	5.76° E	93 m	1000-1800	23-35
SGS	Kaduna	Giwa	9	3	11.316° N	7.450° E	600-650 m	1000-1300	26-38
	Niger	Mokwa, Minna	9	3	9.62° N	6.53° E	168 m	1000-1300	26-38
	Oyo	Shaki	9	3	8.41° N	3.42° E	355-390 m	1000-1300	26-38
	Kwara	Baruten	9	3	8° 54′ N	3° 25′ E	354 m	1000-1300	26-38
NGS	Niger	Babana	9	3	10.436633° N	3.8171953° E	176 m	900-1000	28-40
	Niger	Kontagora	9	3	10.41° N	5.16° E	327 m	900-1000	28-40
	Borno	Maiduguri	9	3	11° 50′ N	13° 09′ E	315-325 m	900-1000	28-40
	Katsina	Sabuwa	9	3	11.17° N	7.12° E		900-1000	28-40
SS	Yobe	Potiskum	9	3	11.7° N	11.08° E	426- 475 m	650-1000	29-41
	Kebbi	Kangiwa	9	3	12.65° N	9.083333° E	630- 650 m	650-1000	29-41
	Sokoto	Shagari	9	3	12° 37′ N	4° 59′ E	264 m	650-1000	29-41
	Jigawa	Roni	9	3	12°30′N −12°45′N	8°15′E – 8°30′E	368 m	650-1000	29-41
SHS	Katsina	Baure	9	3	12.98° N	7.62° E	556 m	450-1050	29-43
	Yobe	Kirikasamma	9	3	12.6927° N	10.308° E	400 m	450-1050	29-43
	Sokoto	Sabon Birni	9	3	12.25° N	4.13° E	325 m	450-1050	29-43
	Jigawa	Guri	9	3	12.7281° N	7° E	334 m	450-1050	29-43
HF	Delta	Agbor	9	3	6.23° N	6.15° E	160 m	1400-2700	22-30
	River	Abonnema	9	3	4.7° N	7.0° E	2 m	1400-2700	22-30
	Delta	Abraka	9	3	5.32° N	6.12° E	18 m	1400-2700	22-30
	Delta	Bonny	9	3	4.40° N	7.14° E	2-3m	1400-2700	22-30

AEZs: Agroecological zones, DS: Derived Savannah, SGS: Southern Guinea Savannah NGS: Northern Guinea Savannah, MA: Mid Altitude, SS: Sudan Savannah, SHS: Sahel Savannah and RF: Humid Forest

Table 2
Methods used to detect mycotoxins on UHPLC.

Methods	Aflatoxins	Ochratoxin A	Zearalenone	Deoxynivalenone
Extraction	80:20 methanol, water	60:40 (*v/v*) acetonitrile, water	60:40 (*v/v*) acetonitrile, water	Dionized water
Standards concentrations	40 ng/ml, 20 ng/mL, 10 ng/mL, 2 ng/mL	10 ppb, 5 ppb, 2 ppb, 0.5 ppb	50 ng/mL, 25 ng/mL, 12.5 ng/mL, 6.25 ng/mL	250 ppb, 500 ppb, 1000 ppb, 2000 ppb
Mobile phase	methanol and water in a (60: 40 v/v)	acetonitrile, water, and acetic acid (51:47:2 v/v)	acetonitrile, water, and methanol (46:46:8 v/v)	water, methanol (15/85 v/v)
Running time	30 min	16-min	17-min	10 min
Excitation/emission wavelength	365 nm/435 nm	333 nm/453 nm	274 nm/455 nm	362 nm/455 nm

(1000 million tonnes) of world's food losses yearly and a substantial part of the wastage is in Africa. Mycotoxins contamination has cost Nigeria huge losses. The financial burden attributed to aflatoxin induced liver cancers in Nigeria due to consumption of sorghum, maize and groundnut is over $4 billion. The economic loss due to ban of Nigerian products between 2007 and 2016 at EU borders due to aflatoxin was $419.4 million USD or 34.6 % non-crude component of trade (Sokefun et al., 2018). The combined impact of fungal contamination in both farmland and stored crops results in a negative international reputation for all agricultural products from the country. The warm and humid climatic conditions in the country favor the growth of mycotoxin-producing fungi during pre- and post-harvest stages, making contamination a persistent challenge (Onyeke, 2020).

While several studies have been conducted to assess mycotoxin contamination in maize from specific regions within Nigeria (Adetuniji et al., 2014; Adetunji et al., 2017; Arifalo et al., 2022; Ayeni et al., 2023), there is a notable lack of comprehensive research examining the occurrence and co-occurrence of mycotoxins in the value chain across the entire country. Furthermore, there has been limited evaluation of the overall dietary risk posed to the Nigerian population from maize consumption at a national level (Adetunji et al., 2017). Given the widespread consumption of maize and its products, understanding the national-scale contamination patterns and associated health risks is essential to ensuring food safety and guiding effective regulatory and mitigation strategies. This study aims to fill this gap by investigating mycotoxin co-occurrence in maize samples representative of Nigeria's diverse agro-ecological zones and assessing the potential dietary risk for the broader population.

2. Materials and methods

2.1. Sample Collection

A total of 270 maize samples were collected during the dry season (February–April 2024) from Nigeria's seven agroecological zones: Derived Savannah (DS), Southern Guinea Savannah (SGS), Northern Guinea Savannah (NGS), Mid Altitude (MA), Sudan Savannah (SS), Sahel Savannah (SHS), and Rain Forest (RF) (Fig. 1). Sampling occurred at four locations per zone (Table 1) from farms, storage facilities, and markets spaced 20 km apart. Locations within each agro-ecological zone (AEZ) were purposively selected based on their representation of major maize-producing districts, characterized by distinct climatic conditions (rainfall and temperature ranges), soil types, and agricultural activity levels as detailed in the provided table. This multistage approach starting with AEZ stratification, followed by state and district selection, and then systematic sampling (9 individual samples per district pooled into 3 composites) ensures coverage of Nigeria's diverse agro-climatic variability. At each sampling site, we randomly collected 1 kg of maize grains from farmers who had grown the crop during the previous season, regardless of visible fungal contamination. Samples were placed in sterile containers, cooled in refrigerated boxes, and transported to the African Centre of Excellence for Mycotoxin and Food Safety (ACEMFS) at Federal University of Technology, Minna, Nigeria. Table 1 details sampling sites and weather conditions. Samples were ground using a sterile mechanical blender (Labinco, Breda, The Netherlands). Per value chain stage (farms, stores, or markets), 9 ground samples were combined into three composites, yielding 90 subsamples total (30 per value chain). These were stored at −20 °C prior to analysis.

2.2. Mycotoxins analysis

2.2.1. Chemical and reagents

All chemicals were of analytical grade and included anhydrous sodium tetraoxosulphate (Na_2SO_4), distilled and deionized water, disodium hydrogen phosphate (Na_2HPO_4), sodium chloride (NaCl), potassium chloride (KCl), potassium dihydrogen phosphate (KH_2PO_4), methanol (MeOH), acetonitrile (MeCN), acetic acid (CH_3COOH), ethanol (EtOH), immunoaffinity columns, and mycotoxin standards.

2.2.2. Phosphate buffered preparation

A phosphate-buffered saline (PBS) solution was prepared by dissolving 0.20 g of potassium chloride, 0.20 g of potassium dihydrogen phosphate, 1.1 g of anhydrous disodium hydrogen phosphate, and 8.00 g of sodium chloride in 900 mL of water. The mixture's pH was adjusted to 7.2 using 0.1 M NaOH and 0.1 M HCl. Distilled water was then added to make the final volume up to 1 L.

2.2.3. Standard preparation

A 5 μg/mL total aflatoxin standard was diluted to a 1 μg/mL intermediate stock. A four-point calibration curve was prepared as follows: Std 4 (80 μL of 1 μg/mL to 2 mL 50% methanol; 40 ng/mL); Std 3 (1 mL Std 4 + 1 mL 50% methanol; 20 ng/mL); Std 2 (1 mL Std 3 + 1 mL 50% methanol; 10 ng/mL); Std 1 (400 μL of 10 ng/mL to 2 mL 50% methanol; 2 ng/mL). A 1000 ng/mL stock (AFB_1, B_2, G_1, G_2) yielded calibration at 40, 20, 10, 2 ng/mL in 50% methanol. Ochratoxin A (5.0 mL, 10.1 μg/mL in acetonitrile) produced intermediate (1000 ppb), working (100 ppb) standards, and calibration (10, 5, 2, 0.5 ppb) in acidified methanol (98/2 v/v methanol/acetonitrile). Zearalenone (5.0 mL, 100 μg/mL in acetonitrile) gave intermediate (1000 ng/mL), working (100 ng/mL) standards, and calibration (50, 25, 12.5, 6.25 ng/mL) in methanol. Deoxynivalenol (1.0 mL, 100 μg/mL in acetonitrile) produced intermediate (1000 ng/mL), working (100 ng/mL) standards, and calibration (250, 500, 1,000, 2000 ppb) in acetonitrile.

2.2.4. Mycotoxin extraction, clean-up, and UHPLC quantification

Mycotoxins were extracted and purified using immunoaffinity columns (IACs; Aflaclean™ for aflatoxins, OchraStar™ R for OTA, ZearaStar™ R for ZEA, DONStar™ R for DON) per manufacturer protocols. AFs (12.5 g maize + 25 mL 80% MeOH, shaken 10 min, centrifuged, 2 mL supernatant diluted 1:7 in PBS); OTA/ZEA (25 g maize + 100 mL 60:40 MeCN/H_2O, shaken 1 h, filtered, 12 mL filtrate diluted 1:4 in PBS pH 7.4); DON (25 g maize + 200 mL deionized water, shaken 30 min, filtered). Extracts were loaded onto IACs at 1–3 mL/min via vacuum pump (Hawach Scientific, GM-0.5B, Shaanxi, China). The Dionex UltiMate 3000 RS UHPLC system analyzed mycotoxins on a C-18 column (5 μm, 4.6 × 150 mm) at 40 °C for aflatoxins, OTA, and ZEA, or 30 °C for DON. All analyses used a 100 μL injection volume (except aflatoxins at 10 μL), a flow rate of 1 mL/min, and fluorescence detection with

Table 3
UHPLC parameters for validating repeatability, precision, recovery, limit of detection (LOD), and limit of quantification (LOQ) for mycotoxins detection.

Toxins	LOD (μg/kg)	LOQ (μg/kg)	Repeatability (%RSD)	Intermediate Precision (%RSD)	Recovery (%)	Linearity (R^2)
AFB_1	0.22	0.64	6.1	12.9	105.2	0.991
AFB_2	0.18	0.49	7.0	14.1	89.6	0.990
AFG_1	0.28	0.81	7.9	13.4	110.2	0.988
AFG_2	0.34	1.10	11.7	13.00	109.3	0.984
OTA	0.32	0.39	5.5	11.00	112.93	0.985
ZEN	5.84	5.98	9.2	18.40	76.17	0.999
DON	4.80	5.34	11.2	17.35	115.32	0.995

* LOD-Limit of detection, LOQ-Limit of quantification, AFB1: Aflatoxin B1, AFB2: Aflatoxin B2, AFG1: Aflatoxin G1, OTA: Ochratoxin A, ZEN: Zearalenone, DON: Deoxynivalenol.

mycotoxin-specific excitation/emission wavelengths. A comprehensive summary of the UHPLC operating conditions for each mycotoxin is shown in Table 2.

2.2.5. Method validation for UHPLC

UHPLC method reliability for maize mycotoxins was validated per Thode (2022) protocol, evaluating linearity, accuracy (% recovery), and sensitivity (LOD). Quantification used external calibration curves from serially diluted standards, acceptable at $r^2 > 0.99$ (Table 3). Accuracy assessed via triplicate recovery: 5 g low-contamination samples fortified with 100 μL calibration standard, thoroughly mixed, equilibrated 24 h at room temperature in fume hood for matrix interaction. LOD/LOQ determined from toxin standard curves using equations (1) and (2) (Thode, 2022).

$$\mathrm{LOD} = \frac{3 \times \textit{standard deviation}}{\textit{slope of calibration curve}} \tag{1}$$

$$\mathrm{LOQ} = 3 \text{ X LOD} \tag{2}$$

The percentage recovery was determined by analysing the spiked samples and comparing them to the blank samples using equation (3) (Thode, 2022).

$$\%\mathrm{Recovery} = \frac{\textit{Concentration measured in spiked sample} - \text{Concentration measured in blank}}{\textit{Spiked amount}} \times 100 \tag{3}$$

2.3. Risk characterization of mycotoxins among maize consumer

Maize consumption by age group was estimated using the FAO/WHO energy-requirement proportional allocation method applied to Nigeria's 2023 food balance sheet data. Per capita maize supply was 31.2 kg/person/year (85.5 g/person/day; FAOSTAT Food Balance Sheets, accessed November 2024). Using Nigeria's 2023 population age structure (United Nations World Population Prospects 2024) and energy requirements relative to adults (18–64 years; 60 kg body weight; FAO/WHO/UNU, 2004) adjusted for infants (0–23 months; 10 kg) and children (2–9 years; 25 kg) adult intake was iteratively solved to match national averages. This yielded mean daily intakes of 35 g/person/day for infants, 62 g/person/day for young children, and 102 g/person/day for adults. This standard method assumes intake proportionality to energy needs absent age-disaggregated surveys (Ayeni et al., 2023).

2.3.1. Estimated Daily Intake

Dietary exposure of the mycotoxins from maize was assessed using the deterministic approach recommended by the Joint FAO/WHO Expert Committee on Food Additives (JECFA, 2001) and EFSA (2006). The Estimated Daily Intake (EDIm) was calculated separately for infants (0–23 months), young children (2–9 years), and adults (≥18 years) using the formula:

$$\mathrm{EDIm} = \frac{\mathrm{Cm} \times \mathrm{K}}{\mathrm{Bw}} \tag{4}$$

Where: *Cm* is the average level of a mycotoxin present in a sample (ng/kg);
k is the daily consumption of sorghum (kg/day)
Bw is the body weight of individuals in kg.

2.3.2. Risk characterization for aflatoxins

For genotoxic and carcinogenic hazards such as aflatoxins, the Margin of Exposure (MOE) approach is recommended for risk assessment. The MOE is obtained by dividing the Benchmark Dose Lower Confidence Limit (BMDL), which is 170 ng kg^{-1} body weight per day, by the estimated dietary exposure. An MOE value lower than 10 000 indicates a possible health concern. This means that an aflatoxin intake greater than 0.017 ng kg^{-1} body weight per day (170 ÷ 10 000) may represent a public health risk.

$$\mathrm{MOE} = \frac{\mathrm{BMDL}}{\mathrm{EDIm}} \tag{5}$$

2.3.3. Estimated liver cancer risk due to consumption of maize grains

The cancer potency values for aflatoxins, as estimated by JECFA, were used to calculate the annual health burden and incidence of hepatocellular carcinoma (HCC) linked to aflatoxin exposure from maize. These values indicate 0.3 cancer cases per 100 000 population per ng/kg body weight per day among individuals infected with hepatitis B virus (HBsAg+), and a value 30 times lower (0.01 cases per 100 000 per ng/kg bw/day) for those uninfected, according to EFSA (2007). The prevalence of HBsAg+ in Nigeria was taken as 8.1% based on prior research. (Badmos et al., 2023).

Using the HBsAg + prevalence rate of 8.1% in Nigeria's total population, the risk of liver cancer was calculated for various population groups consuming maize in the country, following the formulas shown in Equations (6) and (7) respectively.

$$\begin{aligned}\text{Cancer Potency} = {} & 0.3 \times \text{Annual HCC cases } (\mathrm{HBsAgb^{+}}) \\ & + 0.01 \times \text{Annual HCC cases } (\mathrm{HBsAgb^{-}})\end{aligned} \tag{6}$$

$$\text{HCC population Risk} = \mathrm{EDIm} \times \text{Cancer Potency} \tag{7}$$

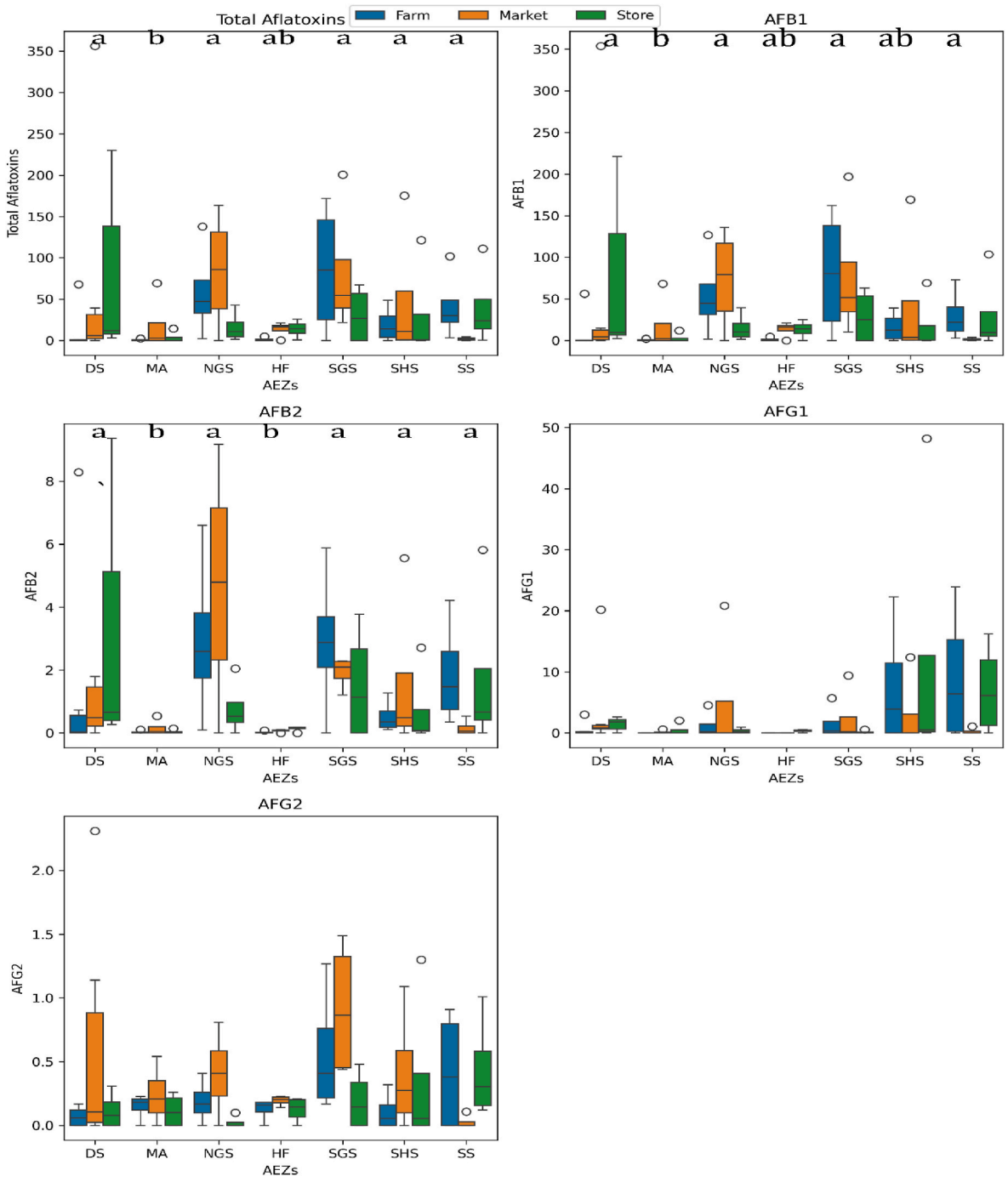

Fig. 2. Distribution of levels of mycotoxins in maize samples from stores, farms, and markets across the seven agroecological zones of Nigeria. Zones labeled with different letters have significant differences ($p<0.05$). The dots, error bars and upper and lower ends of the box repre-sent outliers, spread, and first and third quartiles, respectively.

2.3.4. Risk characterization for non-genotoxic and non-carcinogenic mycotoxins

The risk characterization for non-genotoxic and non-carcinogenic mycotoxins (% Tolerable Daily Intake, TDI) was calculated by dividing the Estimated Daily Intake (EDI) by the Tolerable Daily Intake (TDI) and then multiplying the result by 100, as illustrated in the equation below.

$$\%TDI = \frac{EDIm}{TDIm} \times 100 \quad (8)$$

With TDI for OTA: 17 ng·kg-1 bw·day^{-1}, TDI for DON: 0.25 μg·kg-1 bw·day^{-1} TDI for ZEA: 1 μg·kg-1 bw·day^{-1}

2.4. Statistical data analysis

All maize mycotoxin data from the various agroecological zones were assessed for normality using both the Shapiro–Wilk test and D'Agostino's K^2 test, with the significance level set at 0.05. Since all results showed p-values greater than alpha, the data did not meet the assumptions of normality, and non-parametric statistical methods were therefore applied. The Kruskal–Walli's test was used to evaluate differences among the groups. When the p-value exceeded 0.05, the null hypothesis of no difference was retained. However, for comparisons where the p-value was below 0.05, post-hoc analysis was conducted using

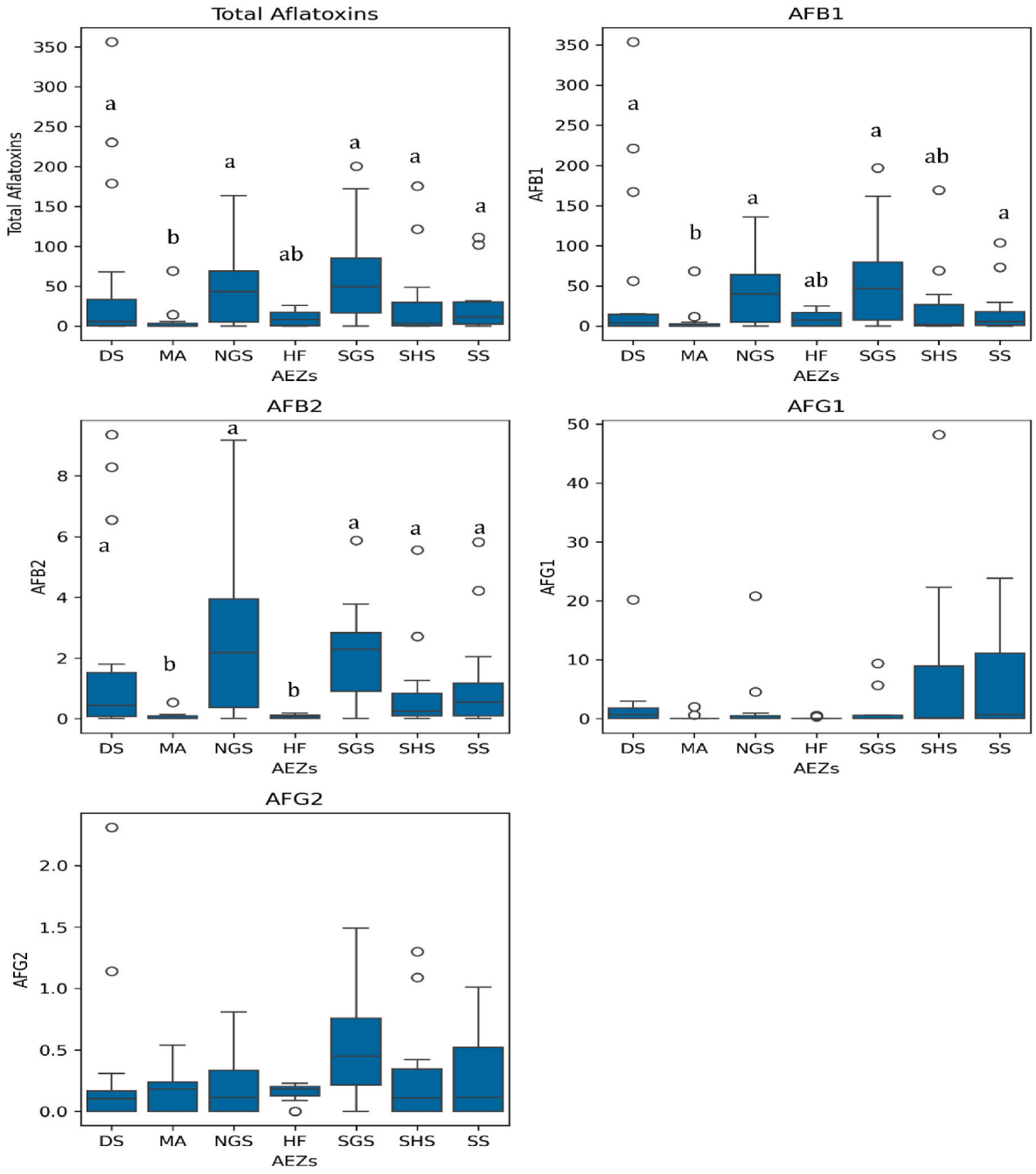

Fig. 3. Distribution of levels of mycotoxins in maize samples across the seven agroecological zones of Nigeria. Zones with different letters have significant differences ($p<0.05$). There were no significant differences amongst the zones for AFG_1 and AFG_2. The dots indicate outliers, the error bars show data spread, and the top and bottom edges of the box represent the third and first quartiles, respectively.

Dunn's test to identify the specific groups that differed from one another.

3. Results and discussion

3.1. Aflatoxin contamination in maize in Nigeria

Fig. 2 presents comparative analysis of total aflatoxins, AFB_1, AFB_2, AFG_1, and AFG_2 across value chain segments and agroecological zones (AEZs). Value chain stage and AEZ significantly influence contamination levels. Market samples in MA and NGS zones show alarmingly high total aflatoxin medians of 100 μg/kg and 75 μg/kg, respectively. DS zone store samples exhibit highest variability, peaking at 350 μg/kg. AFB_1, the most toxic, peaks at 320 μg/kg in DS stores, with MA and NGS markets at 100 μg/kg and 75 μg/kg. Farm-level contamination is lower but notable in NGS and SGS zones (AFB1: 30–70 μg/kg). HF zone consistently records lowest levels across stages, with AFB_1 and total aflatoxins below 10 μg/kg medians. Minor aflatoxins remain low: AFB_2 <10 μg/kg (highest 8 μg/kg in NGS/MA markets); AFG_1 up to 40 μg/kg in SHS/SS stores/farms; AFG_2 <2 μg/kg (1.5–2.0 μg/kg medians in DS/SGS markets). Fig. 3 shows SGS with highest aflatoxin at 66.25 μg/kg (AFB_1: 62.17 μg/kg), followed by NGS (52.95 μg/kg) and DS (51.28 μg/kg) the most contaminated zones with high DS variability. HF and MA exhibit the lowest levels, with MA recording particularly low concentrations.

Aflatoxin contamination in Nigerian maize poses severe public health and economic risks by exceeding safety limits. In Kaduna, 60% of

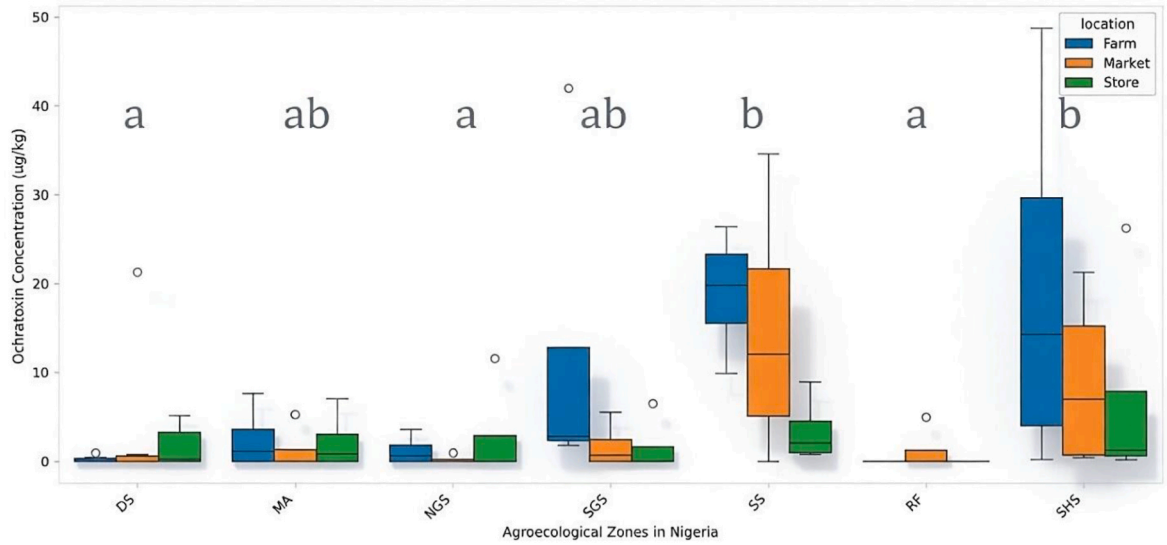

Fig. 4. Distribution of OTA Levels in Maize Samples Across the Seven Agroecological Zones of Nigeria. Zones with different letters have significant differences ($p<0.05$). The dots, error bars and upper and lower ends of the box represent outliers, spread, and first and third quartiles, respectively.

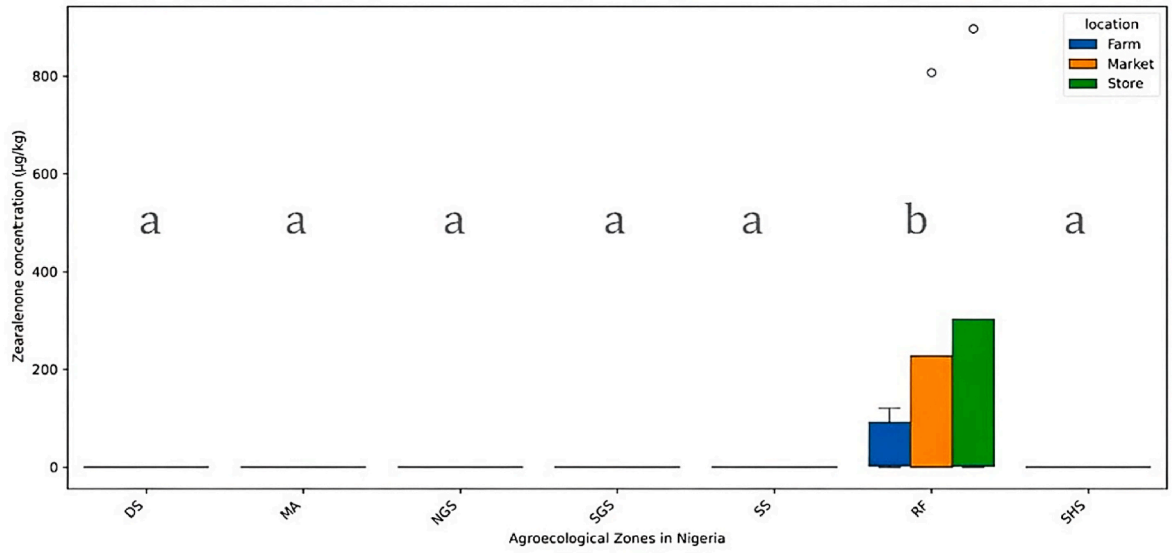

Fig. 5. Distribution of levels of ZEA in maize samples across the seven agroecological zones of Nigeria. Zones marked with different letters indicate significant differences ($p < 0.05$). The dots show outliers, the error bars reflect data variability, and the top and bottom edges of the box indicate the third and first quartiles, respectively.

market samples surpassed NAFDAC's 10 µg/kg limit (6.53–60.87 µg/kg), all exceeding EU/WHO 4 µg/kg due to poor storage (Olaitan et al., 2024). Benue reported 50% sun-dried maize above EU limits from suboptimal agronomy (Mbaawuaga et al., 2020), while Ondo showed 99% contamination (mean: 125.9 µg/kg; max: 265 µg/kg) (Ayeni et al., 2020). Humid zones and practices like delayed drying and permeable sacks promote *Aspergillus flavus* growth (Batagarawa et al., 2015). Biocontrol (Aflasafe™) reduces levels by 91%, but costs, awareness gaps, and weak enforcement limit adoption.

Farm/market samples show higher median aflatoxins than stores due to poor drying, moisture, and handling; stores benefit from sorting/packaging (Atehnkeng et al., 2008; Bankole & Mabekoje, 2004). Southern/Northern Guinea Savanna and Derived Savanna zones suffer most from warm humidity and traditions, while Mid-Altitude/Humid Forest zones fare better with cooler climates/drying (Cardwell et al., 2001; Kpodo et al., 2000). Contamination causes 30% harvest rejections and economic losses, plus liver cancer risk especially for infants (Adetunji et al., 2017; Arifalo et al., 2022).

3.2. *Ochratoxin a contamination in maize in Nigeria*

Fig. 4 illustrates OTA contamination variability across Nigeria's agroecological zones, ranging from non-detectable to over 40 µg/kg. SGS, SS, and SHS zones show highest median and interquartile OTA levels, especially from farm and market sources, statistically distinct from DS, MA, NGS, and HF zones. The latter cluster around 5 µg/kg.

Clear source stratification appears within most AEZs: farm samples have highest medians (particularly SS, SHS), market samples elevate in SS and SGS, while stored maize generally shows lower levels. Exceptions occur in DS and MA, where stored samples slightly elevate. Outliers mark high farm values in SS/SHS, with widest interquartile ranges indicating greater inconsistency there.

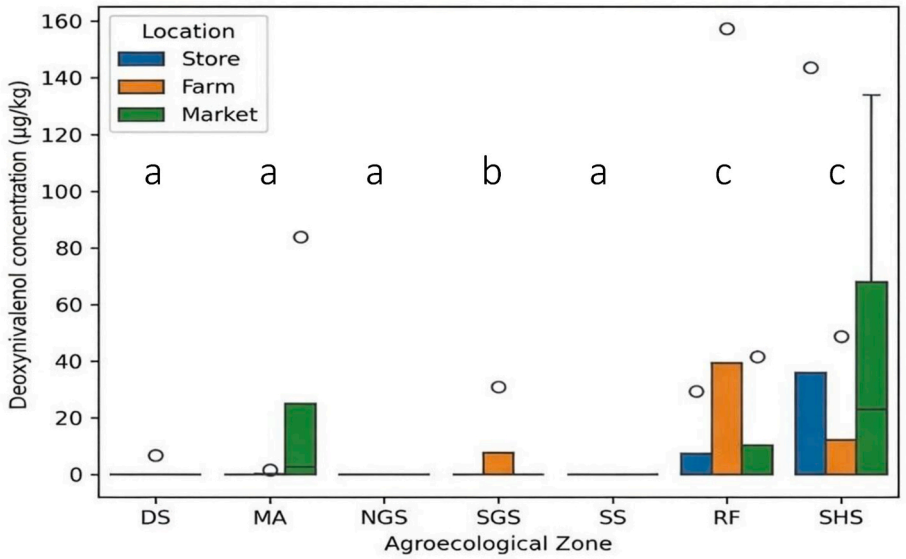

Fig. 6. Distribution of levels of ZEA in maize samples across the seven agroecological zones of Nigeria. Zones marked with different letters indicate significant differences ($p < 0.05$). The dots represent outliers, the error bars indicate data spread, and the upper and lower edges of the box correspond to the third and first quartiles, respectively.

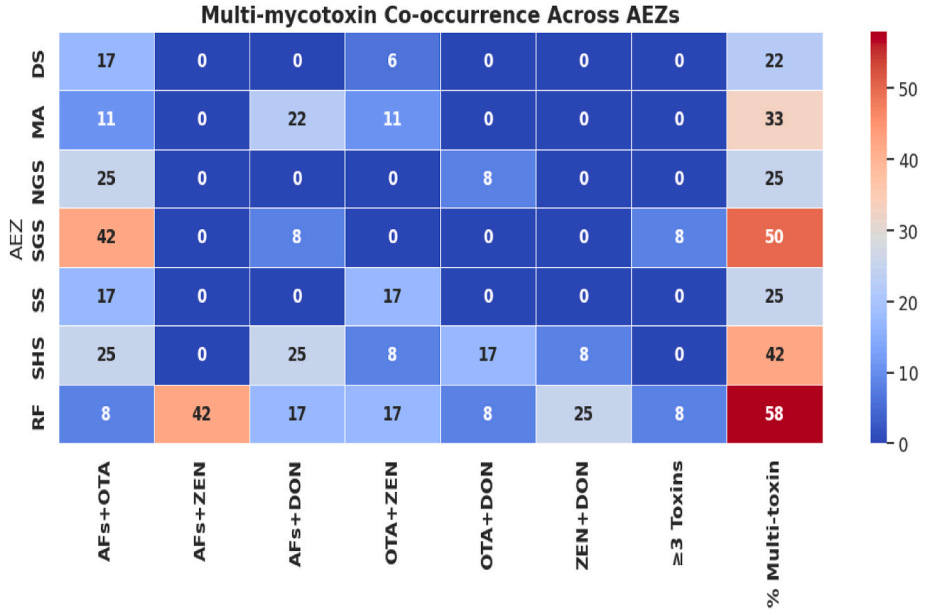

Fig. 7. Multimycotoxins co-occurrence across different agroecological zones
DS: Derived Savannah, NGS: Northern Guinea Savannah, SGS: Southern Guinea Savannah, SS: Soudan Savannah, SHS: Sahel Savannah, MA: Mid Altitude, HF: Humid Forest, AFs: Total aflatoxins, OTA: Ochratoxin A, ZEA: Zearalenone, DON: Deoxynivalenol.

Ochratoxin A (OTA), produced mainly by Aspergillus (*A. ochraceus*, *A. niger*) and *Penicillium* (*P. verrucosum*) fungi, causes nephrotoxicity, immunosuppression, and carcinogenicity (Pitt & Hocking, 2009). Fig. 4 reveals higher OTA levels in farm and market samples than stores in SS and SHS zones, suggesting contamination during pre-market stages from delayed drying and environmental exposure. This emphasizes early post-harvest interventions in high-risk zones. Conversely, RF zone's lower OTA reflects unfavorable conditions for OTA-producers and Fusarium competition suppressing Aspergillus/Penicillium growth (Pitt & Hocking, 2009).

High OTA contamination in SS/SHS threatens public health via kidney disease, immunosuppression, and cancer links (Zinedine et al., 2007). With >25% maize samples exceeding EU limits and >50% positive, urgent targeted interventions are needed, especially in northern savanna zones where maize dominates diets with limited alternatives.

3.3. Zearalenone contamination of maize in Nigeria

Fig. 5 illustrates ZEA concentration distribution in Nigerian maize samples. Most AEZs show non-detectable ZEA levels, except Rainforest (RF) zone with substantially higher contamination across all sample locations. RF exhibits elevated ZEA concentrations, highest in store and market samples with medians surpassing 200 µg/kg and maxima reaching over 800 µg/kg exceeding EU limits, while farm levels remain relatively lower. RF differs significantly ($p < 0.05$) from other zones.

Table 4
Prevalence and regulatory exceedance of mycotoxins in nigerian maize by agro-ecological zones.

Agroecological Zones	N samples	Total aflatoxins range (μg/kg)	Mean ± SEM	% positive samples (Aflatoxins)	% >EU limit (Aflatoxins)	% >NAFDAC limit (Aflatoxins)	OTA range (μg/kg)	Mean±SED	% positive samples (OTA)	% >EU limit (OTA)	ZEA range (μg/kg)	Mean ± SEM	% positive samples (ZEA)	% >EU limit (ZEA)	DON range (μg/kg)	Mean ± SEM	% positive samples (DON)	% >EU limit (DON)
DS	18	0.12-356.16	49.51 ± 17.84	100.0	55.55	33.33	<LOD -21.32	1.85 ± 1.18	38.88	11.11	<LOD	<LOD	0.0	0.0	<LOD -6.68	0.37 ± 0.37	5.55	0
NGS	12	<LOD -163.42	48.33 ± 13.96	91.66	75.0	66.66	<LOD -11.58	1.45 ± 0.98	41.66	8.33	<LOD	<LOD	0.0	0.0	<LOD	<LOD	0.0	0
SGS	12	<LOD -200.51	79.40 ± 20.74	91.66	75.0	75.0	0-41.99	5.15 ± 3.42	58.33	25.0	<LOD	<LOD	0.0	0.0	0-30.96	2.58 ± 2.58	8.33	0
SS	12	<LOD -111.21	33.31 ± 11.92	91.66	58.33	50.0	<LOD 34.60	11.76 ± 3.45	91.66	66.66	<LOD	<LOD	0.0	0.0	<LOD	<LOD	0.0	0
SHS	12	0.2-175.36	39.75 ± 16.78	100.0	50.0	41.66	0.21-48.75	11.85 ± 4.28	100.0	41.66	<LOD	<LOD	0.0	0.0	<LOD -143.64	31.02 ± 14.86	33.33	0
MA	12	<LOD -69.29	7.79 ± 5.92	66.66	25.0	16.66	<LOD -7.62	2.07 ± 0.84	41.66	25.0	<LOD	<LOD	0.0	0.0	0-83.93	7.56 ± 6.95	25.0	0
HF	12	0.14-25.91	9.78 ± 2.70	100.0	58.33	50.0	<LOD -4.98	0.42 ± 0.42	8.33	0.0	0-897.02	238.88 ± 86.53	66.66	6.66	<LOD -157.36	19.03 ± 13.38	25.0	0
Total	90	<LOD -356.16	39.58 ± 6.40	92.22	56.66	46.66	<LOD -48.75	4.51 ± 1.02	52.22	25.55	0-897.02	31.85 ± 11.59	8.88	2.22	<LOD -157.36	8.28 ± 3.31	13.33	0

DS: Derived Savannah, NGS: Northern Guinea Savannah, SGS: Southern Guinea Savannah, SS: Soudan Savannah, SHS: Sahel Savannah, MA: Mid Altitude, HF: Humid Forest, SD: Standard Deviation, EU: European Union, NAFDAC: National Agency for Food and Drug Administration and Control, OTA: Ochratoxin A, ZEA: Zearalenone, DON: Deoxynivalenol. <LOD: Les than the limit of detection.

Table 5
Prevalence and Regulatory Exceedance of Mycotoxins in Nigerian Maize by Sampling site.

Sampling point	N samples	Total aflatoxins range (μg/kg)	Mean ± SD	% positive samples (Aflatoxins)	% >EU limit (Aflatoxins)	% >NAFDAC limit (Aflatoxins)	OTA range (μg/kg)	Mean ± SD	% positive samples (OTA)	% >EU limit (OTA)	ZEA range (μg/kg)	Mean ± SD	% positive samples (ZEA)	% >EU limit (ZEA)	DON range (μg/kg)	Mean ± SD	% positive samples (DON)	% >EU limit (DON)
Stores	30	<LOD -230.2	52.62 ± 13.02	90.0	60.0	50.0	<LOD -26.25	4.24 ± 1.34	43.33	20.0	0-897.02	77.42 ± 35.82	10.0	0.03	<LOD -143.64	2.36 ± 1.63	6.66	0
Farms	30	<LOD -171.91	36.48 ± 9.87	96.66	46.66	40.0	<LOD -48.75	6.90 ± 2.09	60.0	30.0	0-69.65	8.94 ± 5.89	10.0	0.0	<LOD -157.36	13.88 ± 7.47	16.66	0
Markets	30	<LOD -356.16	29.63 ± 8.41	90.0	63.33	50.0	<LOD -34.60	2.40 ± 0.91	46.66	23.33	0-807.06	69.35 ± 58.14	6.66	0.03	<LOD -133.90	8.61 ± 5.84	16.66	0
Total	90	<LOD -356.16	39.58 ± 6.40	92.22	56.66	46.66	<LOD -48.75	4.51 ± 1.02	52.22	25.55	0-897.02	31.85 ± 11.59	8.88	2.22	<LOD -157.36	8.28 ± 3.31	13.33	0

DS: Derived Savannah, NGS: Northern Guinea Savannah, SGS: Southern Guinea Savannah, SS: Soudan Savannah, SHS: Sahel Savannah, MA: Mid Altitude, HF: Humid Forest, SD: Standard Deviation, EU: European Union, NAFDAC: National Agency for Food and Drug Administration and Control, OTA: Ochratoxin A, ZEA: Zearalenone, DON: Deoxynivalenol. <LOD: Less than the limit of detection.

Table 6
Exposure assessment and estimated liver cancer risk due to consumption of maize grains.

AEZs	Total Aflatoxins (ng/g)	EDI (ng·kg^{-1} bw·day^{-1})			MOE			Liver Cancer Risk (cases/yr/100 000)		
		Infants	Children	Adults	Infants	Children	Adults	Infants	Children	Adults
NGS	48.33	169.2	119.7	82.2	1.01	1.42	2.07	7.22	5.11	3.51
SGS	79.40	278.0	196.7	135.0	0.61	0.86	1.26	11.86	8.39	5.76
SS	33.31	116.6	82.5	56.6	1.46	2.06	3.00	4.98	3.52	2.42
SHS	39.75	139.1	98.4	67.6	1.22	1.73	2.51	5.94	4.20	2.89
DS	49.51	173.3	122.6	84.1	0.98	1.39	2.02	7.40	5.24	3.59
MA	7.79	27.3	19.3	13.3	6.23	8.81	12.78	1.17	0.82	0.57
HF	9.78	34.2	24.2	16.6	4.97	7.02	10.24	1.46	1.03	0.71
National	39.58	138.5	98.0	67.3	1.23	1.73	2.53	5.91	4.18	2.87

AEZs: Agroecological zones, DS: Derived Savannah, NGS: Northern Guinea Savannah, SGS: Southern Guinea Savannah, SS: Soudan Savannah, SHS: Sahel Savannah, MA: Mid Altitude, HF: Humid Forest, OTA: Ochratoxin A, ZEA: Zearalenone, DON: Deoxynivalenol.

High ZEA contamination in the RF zone arises from environmental and post-harvest factors. High rainfall and humidity foster *Fusarium* infection during maize cultivation, promoting fungal growth and ZEA biosynthesis under flowering/kernel stress (Magan & Aldred, 2007). Fig. 6 shows ZEA escalation from farm to market/store samples in RF, due to poor drying, inadequate storage, and prolonged market durations enabling post-harvest Fusarium growth (Makun et al., 2013).

These align with Nigerian studies: Ezekiel et al. (2012) found higher ZEA in southern (RF-inclusive) maize than the drier north; Bankole and Mabekoje (2004) tied ZEA to humid forest *Fusarium*; Adetunji *et al.* (2014) and Makun et al. (2013) noted poor storage pushing market/-store levels beyond limits.

RF's elevated ZEA threatens public health/food security via estrogenic effects, disrupting reproduction in women/children and raising cancer risk (Zinedine et al., 2007). Market/store samples, widely consumed, pose the greatest concern.

3.4. Deoxynivalenol contamination in maize in Nigeria

Fig. 6 shows strong spatial variability in DON distribution across Nigerian agroecological zones from stores, farms, and markets. DON was undetectable in dry zones (DS, NGS, SS). Moderate contamination occurred in MA (market samples averaging 25 μg/kg with outlier at 85 μg/kg; farms/stores undetectable) and SGS (mainly farms at 8 μg/kg). Most concerning was humid zones RF and SHS. RF exhibited highest DON, with farms averaging 40 μg/kg, stores/markets 8-12 μg/kg, but market outliers exceeding 140 μg/kg and farm outliers exceeding 160 μg/kg. SHS showed highest overall burden: markets averaging 68 μg/kg (extremes at 135 μg/kg), stores 36 μg/kg, farms 12 μg/kg.

Elevated DON contamination in RF and SHS zones stems primarily from favorable environments for Fusarium growth and mycotoxin production. Nigeria's RF zone, with high humidity, warm temperatures, and frequent rainfall, provides ideal conditions for Fusarium infection, where moisture drives fungal proliferation and DON biosynthesis during grain filling and post-harvest (Olopade et al., 2021). Similarly, SHS zones experience fluctuating stresses—dry periods alternating with torrential rains exacerbated by suboptimal drying, erratic storage, and heat in markets/warehouses, promoting post-harvest toxin accumulation (Adie et al., 2022). This explains higher DON in market/store samples versus farms.

These patterns highlight critical control points: farms start with moderate contamination, but improper handling, delayed drying, and aggregation in unsanitary markets foster fungal resurgence (Olopade et al., 2021). This study's zoning aligns with prior Nigerian research Southwest showing low-moderate DON with peaks above thresholds (Olopade et al., 2021), and Makurdi markets exceeding limits due to moisture/hygiene (Adie et al., 2022) emphasizing regional heterogeneity.

3.5. Co-occurrence of mycotoxins contamination in maize in Nigeria

Fig. 7 shows the multimycotoxins co-occurrence across different agroecological zones in Nigeria. In maize from the RF zone, 42% of samples were co-contaminated with AFs + ZEA, 25% with ZEA + DON, and 17% with AFs + DON, giving the highest overall multi-toxin prevalence (58% of samples with ≥2 toxins) among all agroecological zones. In the Southern Guinea Savannah (SGS), 42% of samples were co-contaminated with AFs + OTA and 8% with AFs + DON, while an additional 8% harbored three or more mycotoxins resulting in 50% multi-contaminated samples overall. The Sahel (SHS) also showed important co-occurrence, with 25% AFs + DON, 17% OTA + DON, 8% ZEA + DON and 42% multi-toxin samples, while DS, MA, NGS and SS had lower multi-toxin burdens (22–33%), typically dominated by a single toxin pair such as AFs + OTA in DS (17%) or AFs + DON in MA (22%). These findings highlight RF, SGS, and SHS as critical hotspots for complex mycotoxin mixtures in Nigerian maize, warranting prioritized intervention.

The high multi-mycotoxin co-occurrence in maize from several agroecological zones, heighten health risks as AFs, OTA, ZEA, and DON interact additively, synergistically, or antagonistically *in vivo* rather than acting independently. RF (58% multi-toxin samples: 42% AFs + ZEA, 25% ZEA + DON), SGS (50% multi-toxin: 42% AFs + OTA, some ≥3-toxin), and SHS (42% multi-toxin: 25% AFs + DON, 17% OTA + DON, 8% ZEA + DON) emerge as hotspots of mixed exposures.

Toxicologically, AFs with DON or ZEA potentiate genotoxicity, oxidative stress, immunosuppression, and growth impairment beyond single-toxin effects (Fusilier et al., 2022). DON enhances AFB1/ZEA toxicity, while AFs + OTA aggravate liver/kidney damage, showing additive/synergistic interactions at dietary doses (Thapa et al., 2021). In Nigeria's hepatitis B/malnutrition-prevalent areas, such combinations elevate hepatocellular carcinoma, child growth impairment, immune dysfunction, and reproductive disorder risks (Giorni et al., 2019).

SGS/RF ≥ 3-toxin samples are particularly alarming, as mixture toxicology reveals combined hazard indices exceeding thresholds despite individual compliance (Weaver et al., 2021). Current single-toxin standards fail to address RF/SGS/SHS cocktail exposures lacking established safe levels.

3.6. Prevalence and regulatory exceedance of mycotoxins in nigerian maize by agro-ecological zones

In the DS, total aflatoxins occurred in all samples, averaging 49.51 ± 17.84 μg/kg and peaking at 356.16 μg/kg, with 55.6% exceeding the EU limit of 10 μg/kg and 33.3% surpassing NAFDAC's 20 μg/kg. OTA appeared in 38.9% at 1.85 ± 1.18 μg/kg (11.1% > EU), ZEA was absent, and DON nearly undetectable. NGS exhibited high aflatoxins (48.33 ± 13.96 μg/kg; 75% > both limits) and OTA in 41.7%. SGS showed highest aflatoxins (79.40 ± 20.74 μg/kg; 75% > limits) with OTA in 58.3% (25% exceeding EU limits). SS had widespread aflatoxins (33.31 ± 11.92 μg/kg) and prevalent OTA (11.76 ± 3.45 μg/kg), both exceeding

Table 7
Risk characterization of Non-genotoxic and Non-carcinogenic Mycotoxins based on Tolerable Daily Intake.

AEZs	Mean OTA (μg/kg)	EDI			%TDI			Mean ZEA (μg/kg)	EDI			%TDI			Mean DON (μg/kg)	EDI			%TDI		
		Infants	Children	Adults	Infants	Children	Adults		Infants	Children	Adults	Infants	Children	Adults		Infants	Children	Adults	Infants	Children	Adults
DS	1.45	6475	4588	3145	38 090	27 000	18 500	<LOD	0	0	0	0	0	0	0.37	1295	918	629	130	92	63
NGS	1.45	5075	3596	2465	29 850	21 150	14 500	<LOD	0	0	0	0	0	0	<LOD	0	0	0	0	0	0
SGS	5.15	18 025	12 772	8755	106 030	75 130	51 500	<LOD	0	0	0	0	0	0	2.58	9030	6398	4386	903	640	439
SS	11.76	41 160	29 165	19 992	242 120	171 560	117 600	<LOD	0	0	0	0	0	0	<LOD	0	0	0	0	0	0
SHS	11.85	41 475	29 388	20 145	243 970	172 870	118 500	<LOD	0	0	0	0	0	0	31.02	108 570	76 930	52 734	10 857	7693	5273
MA	2.07	7245	5134	3519	42 620	30 200	20 700	<LOD	0	0	0	0	0	0	7.56	26 460	18 749	12 852	2646	1875	1285
HF	0.42	1470	1042	714	8650	6130	4200	238.88	836 080	592 422	406 096	334	237	162	19.03	66 605	47 194	32 351	6661	4719	3235
National	5.75	19 500	13 800	9500	115 000	81 000	56 000	14.3	50 000	35 500	24 300	20	14	10	5.15	18 000	12 800	8800	1800	1280	880

AEZs: Agroecological zones, DS: Derived Savannah, NGS: Northern Guinea Savannah, SGS: Southern Guinea Savannah, SS: Soudan Savannah, SHS: Sahel Savannah, MA: Mid Altitude, HF: Humid Forest, OTA: Ochratoxin A, ZEA: Zearalenone, DON: Deoxynivalenol, EDI: Estimated daily intake. TDI: Tolerable daily intake.

EU limits in over half. Sahel Savannah (SHS) displayed universal aflatoxins (39.75 ± 16.78 μg/kg; 50% exceeding EU limits), OTA in all (41.7% exceeding > EU limits), and DON in 33%. Mid-Altitude (MA) recorded lowest aflatoxins (7.79 ± 5.92 μg/kg) with modest OTA/DON, while HF showed low aflatoxins (9.78 ± 2.70 μg/kg), minimal OTA, but high ZEA (238.88 ± 86.53 μg/kg; some exceeding EU limits). Nationally, aflatoxins averaged 39.58 ± 6.40 μg/kg, with 56.7% > EU and 46.7% exceeding NAFDAC limits. Prevalence data across zones are summarized in Table 4.

3.7. Prevalence and regulatory exceedance of mycotoxins in nigerian maize by sampling site

Among 30 store maize samples, total aflatoxins ranged from below detection to 230.2 μg/kg, averaging 52.62 ± 13.02 μg/kg; 90% were contaminated, with 60% exceeding EU limits and 50% surpassing NAFDAC thresholds. OTA appeared in 43.3% of stores, averaging 4.24 ± 1.34 μg/kg (20% > EU limit). ZEA occurred in 10% at 77.42 ± 35.82 μg/kg (extreme 897 μg/kg), while DON was rare/low (2.36 ± 1.63 μg/kg). Samples from farms showed average aflatoxin concentration 36.48 ± 9.87 μg/kg (<LOD–171.91; 96.7% positive, ~50% > EU), highest OTA (6.90 ± 2.09 μg/kg; 30% > EU), ZEA in 10%, and DON in 16.7% (13.88 ± 7.47 μg/kg). Samples from markets had widest aflatoxin concentration range (<LOD–356.16 μg/kg; mean 29.63 ± 8.41; 90% positive, 63.3% > EU), OTA in 46.7% (23.3% > EU), rare/extreme ZEA (69.35 ± 58.14 μg/kg), and DON in 16.7%. Table 5 summarizes mycotoxin levels above regulatory limits by location.

3.8. Exposure and risk assessment among the different population groups that consume maize in Nigeria

3.8.1. Risk assessment for aflatoxins

In Nigeria's diverse agro-ecological zones (AEZs), aflatoxin exposure shows significant spatial and age-related variation. The SGS reports the highest total aflatoxin concentration of 79.40 ng/g, with infants facing peak EDI of 278.0 ng kg^{-1} bw·day^{-1}, children 196.7, and adults 135.0. These yield critically low MOE values 0.61 for infants, 0.86 for children, 1.26 for adults all below 10 000, signaling major health risks. Liver cancer risks peak in SGS at 11.86 cases per 100 000 infants annually.

Contrastingly, MA zone exhibits lowest contamination (7.79 ng/g), safer EDI/MOE, and minimal cancer risks. HF shows moderate levels, while NGS (48.33 ng/g) and DS (49.51 ng/g) approach SGS risks, with infant EDI at 169.2 and 173.3 ng kg^{-1} bw·day^{-1}, and MOE of 1.01/0.98. Sudan/SHS display intermediate profiles. Nationally, 39.58 ng/g averages heighten infant risks due to high relative intake. Table 6 shows estimated liver cancer risks from maize consumption.

Infants face the highest aflatoxin exposure risk from Nigerian maize due to elevated intake relative to body weight (Adetunji et al., 2017), yielding critically low MOE values like 0.61 in SGS and liver cancer estimates up to 11.86 cases/100 000 annually. Chronic AFB1 exposure, a potent hepatocarcinogen linked to HCC, is amplified 30-fold by Nigeria's 13.2% hepatitis B prevalence (Adetunji et al., 2017). Beyond cancer, it causes acute aflatoxicosis liver failure, jaundice, immunosuppression, stunting, neurodevelopmental harm, and death (Adaku Chilaka and Mally, 2020; Adetunji et al., 2017).

SGS poses the greatest threat with 278 ng/g concentrations, exceeding national averages (138.5 ng/g) and other zones, while humid forests show lower risks. These align with studies attributing 2600–5000 annual liver cancer deaths and child impairments to maize (Adaku Chilaka and Mally, 2020). National MOE <3 signals crisis, urgently requiring interventions in SGS to prevent hepatic damage and oncogenesis (Adetunji et al., 2017; Adaku Chilaka and Mally, 2020).

3.8.2. Risk characterization of non-genotoxic and non-carcinogenic mycotoxins based on tolerable daily intake

Ochratoxin A (OTA) contamination in Nigeria's agro-ecological

zones (AEZs) peaks in Southern Humid Savanna (SHS; 11.85 μg/kg) and Sudan Savanna (11.76 μg/kg), driving extreme infant EDI to 41 475 and 41 160 ng kg^{-1} bw·day^{-1} respectively over 240 000% of the 17 ng kg^{-1} bw·day^{-1} TDI. Southern Guinea Savanna (SGS) shows moderate OTA (5.15 μg/kg; infant EDI 18 025 ng kg^{-1} bw·day^{-1}, >100 000% TDI), while Derived/Northern Guinea Savannas (1.45 μg/kg) and Mid-Altitude (2.07 μg/kg) register lower risks, with Humid Forest (HF; 0.42 μg/kg) safest yet still exceeding TDI by thousands of percent for infants. Nationally, OTA averages 5.75 μg/kg, with infants at 115 000% TDI. Zearalenone (ZEA) is negligible except in HF (238.88 μg/kg; infant %TDI 334%), while deoxynivalenol (DON) peaks in SHS (31.02 μg/kg; 10 857% TDI infants), followed by HF (19.03 μg/kg; 6661%) and MA (7.56 μg/kg; 2646%). Infants face highest exposures across mycotoxins due to body weight-adjusted intake, highlighting SHS as multi-mycotoxin hotspot. Table 7 presents risk characterization of non-genotoxic and non-carcinogenic mycotoxins based on tolerable daily intake in the different zones.

Elevated mean concentrations of non-genotoxic mycotoxins OTA, ZEA, and DON in Nigerian maize AEZs pose significant health risks, particularly to infants and children with highest EDI relative to %TDI. Chronic OTA exposure, prominent in savanna zones like SHS and DS, causes nephrotoxicity and immunosuppression, risking kidney damage, developmental delays, and immune dysfunction in young children (Wenndt et al., 2023; Adetunji *et al.*, 2014). Similarly, high ZEA in humid forests disrupts endocrine function through estrogenic effects, impacting hormonal balance and reproductive development during infancy (Akinleye et al., 2025; Wenndt et al., 2023).

DON prevalence in SHS and HF zones threatens dietary toxicity nausea, vomiting, gastrointestinal/immune compromise critical for infants' vulnerable detoxification (Adetunji et al., 2017). Consistent TDI exceedances across AEZs, combined with aflatoxin co-occurrence, amplify cumulative effects on child growth, immunity, and long-term health (Nnamani et al., 2024). As maize dominates infant nutrition, urgent surveillance, interventions in high-risk AEZs, and policy enforcement are essential (Adetunji et al., 2017; Adaku and Mally, 2020).

4. Conclusion

This study reveals pervasive mycotoxin contamination in Nigerian maize across seven agro-ecological zones (AEZs), with aflatoxins (mean 39.58 μg/kg) detected in 92.2% of samples—56.7% exceeding EU limits and OTA (4.51 μg/kg), ZEA (31.85 μg/kg), and DON (8.28 μg/kg) showing zone-specific hotspots: SGS for aflatoxins (79.40 μg/kg), SS/SHS for OTA (11.76-11.85 μg/kg), HF for ZEA (238.88 μg/kg), and SHS/HF for DON (31.02-19.03 μg/kg). Infants face the gravest risks, with aflatoxin EDI up to 278 ng/kg bw/day (MOE 0.61 in SGS; cancer risk 11.86 cases/100 000/year), OTA %TDI at 243 970% (SHS), ZEA 836 080% (HF), and DON 10 857% (SHS), driven by higher relative intake and immature detoxification. Addressing mycotoxin contamination in Nigerian maize requires targeted interventions to reduce exposure and health risks. Timely harvesting and adequate drying minimize fungal growth, while hermetic, moisture-controlled storage prevents post-harvest toxin buildup. Sorting damaged grains and decontamination further safeguard supplies. Awareness programs empower farmers, traders, and consumers with safer practices, complemented by biocontrol like Aflasafe™ against aflatoxin producers. Stronger EU/NAFDAC enforcement, ongoing monitoring, and local lab investments enable timely detection. These protect high-risk zones and vulnerable infants, enhancing nationwide food safety. A key limitation excludes fumonisins—prevalent in Nigerian maize, often exceeding limits, and linked to esophageal cancer and neural tube defects—necessitating future HPLC analysis for full risk assessment.

CRediT authorship contribution statement

Edzili Awono Antoine Thierry: Writing – original draft. **Ifeanyi Famous Ossamulu:** Writing – review & editing. **Maimuna Habib:** Validation. **Dogo Eustace:** Supervision. **Hadiza Lami Muhammad:** Project administration. **Jean Justin Essia Ngang:** Supervision. **Hussaini Anthony Makun:** Supervision, Funding acquisition.

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Declaration of competing interest

I have nothing to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodcont.2026.112201.

Data availability

Data will be made available on request.

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