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Research Article

Occurrence and Human Health Risk Assessment of Pesticide Residues in Staple Cereals Sold in Northern Nigeria

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Abstract

Pesticide contamination of cereal grains has become a growing food safety concern because cereals constitute a major component of the human diet and represent an important route of dietary exposure to agrochemical residues. This study investigated the occurrence of pesticide residues in commonly consumed cereals marketed in northern Nigeria, determined their compliance with maximum residue limits (MRLs), and evaluated the associated non-carcinogenic health risks to adults and children. Composite samples of beans, sorghum, maize, wheat, local rice, and imported rice were collected from representative markets and analysed using high-performance liquid chromatography (HPLC). Exceedance factors (EFs) were calculated by comparing measured concentrations with established MRLs, comparing pesticide residue concentrations among cereal types using one-way analysis of variance followed by Tukey's Honestly Significant Difference (HSD) post hoc test where appropriate, and assessing the associated non-carcinogenic health risks for adults and children through ingestion, inhalation, and dermal exposure pathways. Four pesticide residues, imidacloprid, acetamiprid, pendimethalin, and propiconazole, were detected at concentrations ranging from 0.06 to 0.90 mg kg^{-1}. All detected residues exceeded their respective MRLs, with exceedance factors ranging from 1.2 to 18.0. Pendimethalin exhibited the highest contamination in maize (0.90 mg kg^{-1}; EF = 18.0), followed by local rice (0.86 mg kg^{-1}; EF = 17.2) and sorghum (0.85 mg kg^{-1}; EF = 17.0), whereas wheat contained the highest imidacloprid concentration (0.73 mg kg^{-1}; EF = 14.6). One-way analysis of variance (ANOVA) indicated significant differences in imidacloprid concentrations among the cereal types ($p < 0.05$). Tukey's Honestly Significant Difference (HSD) post hoc test further revealed that wheat contained significantly higher imidacloprid concentrations than beans, sorghum, maize, and local rice ($p < 0.001$). Despite these exceedances, all estimated HQ and HI values for adults and children remained below the acceptable safety threshold of 1.0, indicating negligible non-carcinogenic health risks under the current exposure scenarios. Children consistently exhibited higher exposure estimates than adults due to lower body weight and greater intake relative to body mass. The widespread occurrence of pesticide residues above regulatory limits highlights the need for strengthened pesticide management, routine surveillance, and improved compliance with good agricultural practices. Continuous monitoring remains essential to minimise dietary exposure and ensure consumer safety.

Introduction

Cereals constitute the principal staple foods for more than half of the world's population and provide a substantial proportion of daily dietary energy, particularly in low- and middle-income countries. In sub-Saharan Africa, cereals such as maize, sorghum, millet, rice, and wheat play indispensable roles in food security, nutrition, and socioeconomic development. Nigeria is among the largest producers and consumers of cereals in Africa, where these crops serve as primary sources of carbohydrates, dietary fibre, vitamins, minerals, and phytochemicals essential for human health [1]. Owing to their high consumption rates across all age groups, contaminants present in cereals can significantly contribute to long-term dietary exposure and consequently pose important public health concerns.

The widespread use of pesticides has undoubtedly improved crop productivity and reduced post-harvest losses. Nevertheless, inappropriate pesticide application practices, including excessive dosage, repeated spraying, poor adherence to pre-harvest intervals, and improper storage, may result in

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pesticide residues remaining in harvested food commodities. These residues may persist throughout processing and distribution and ultimately enter the human food chain through dietary consumption [2,3]. Several classes of pesticides, including neonicotinoids, organophosphates, carbamates, pyrethroids, fungicides, and herbicides, have frequently been detected in cereals marketed in developing countries, raising concerns regarding food safety and consumer health [4].

Dietary exposure to pesticide residues has become an important global public health issue because cereals are consumed daily and in relatively large quantities [5,6]. Chronic exposure, even at low concentrations, has been associated with adverse health outcomes including neurotoxicity, endocrine disruption, reproductive disorders, developmental abnormalities, immunotoxicity, and increased risks of certain cancers. Children are particularly vulnerable because of their lower body weight, higher food consumption relative to body mass, and developing physiological systems [7,8,9]. Consequently, international regulatory agencies such as the Codex Alimentarius Commission and the WHO have established maximum residue limits (MRLs) and toxicological reference values to protect consumers from excessive pesticide exposure [10].

Nigeria is one of Africa's largest producers and consumers of cereals, yet the increasing reliance on agrochemicals has raised concerns regarding pesticide contamination of food commodities [11]. Several studies have reported detectable pesticide residues in cereals and other agricultural products sold in Nigerian markets, with some residues exceeding established MRLs, thereby indicating potential risks to consumers [12-15]. Despite these findings, surveillance remains limited in many parts of Northern Nigeria, where cereals constitute the principal staple food and information on the occurrence of multiple pesticide residues and associated human health risks remains scarce.

Assessment of pesticide residues alone does not provide sufficient information regarding their implications for public health. Human health risk assessment integrates measured residue concentrations with food consumption rates and toxicological reference values to estimate dietary exposure and characterise both non-carcinogenic and carcinogenic risks [16]. Such assessments provide scientific evidence that supports food safety regulation, public health interventions, pesticide management policies, and continuous monitoring programs aimed at protecting consumers while promoting sustainable agricultural production.

Therefore, the present study was undertaken to determine the occurrence and concentrations of pesticide residues in commonly consumed cereals marketed in northern Nigeria, evaluate compliance with established Maximum Residue Limits using the exceedance factor approach, compare pesticide residue concentrations among cereal types using one-way analysis of variance followed by Tukey's Honestly Significant Difference (HSD) post hoc test where appropriate, and assess the associated non-carcinogenic health risks for adults and children through ingestion, inhalation, and dermal exposure pathways. The findings are expected to provide valuable baseline information for food safety authorities, regulatory agencies, agricultural extension services, and policymakers to strengthen pesticide management strategies, improve residue surveillance programmes, and protect public health through evidence-based decision-making.

Materials and methods

Study area

This study was conducted in Northern Nigeria, a major agricultural region characterised by extensive cultivation and marketing of staple cereals, including maize (*Zea mays*), sorghum (*Sorghum bicolour*), wheat (*Triticum aestivum*), rice (*Oryza sativa*), and beans (*Phaseolus vulgaris*). These cereals constitute important dietary staples and are widely consumed by both rural and urban populations. Samples were obtained from major markets that receive produce from different farming communities across the region, thereby providing representative information on pesticide residues in cereals available to consumers.

Sample collection

Representative cereal samples comprising maize, sorghum, wheat, local rice, foreign rice, and beans were collected from major cereal markets in northern Nigeria using a randomised sampling approach. Approximately 1 kg of each cereal sample was purchased from different vendors to ensure representativeness and minimise sampling bias [17]. Samples were individually packaged in clean polyethene bags, properly labelled, transported to the laboratory under appropriate conditions, and stored at 4°C until analysis.

Sample preparation

In the laboratory, foreign materials such as stones, husks, and other debris were removed manually. The cereal samples were air-dried where necessary before being ground into fine powder using a stainless-steel laboratory grinder. The powdered samples were passed through a 2-mm stainless-steel sieve to obtain uniform particle size. Prepared samples were stored in clean paper bags at room temperature until extraction and analysis.

Extraction of pesticide residues (quechers method)

Pesticide residues were extracted using the QuEChERS (Quick, Easy, Cheap, Effective, Rugged and Safe) method, which is widely recommended for multi-residue pesticide analysis in food matrices. Approximately 10g of homogenised cereal sample was weighed into a 50-mL polypropylene centrifuge tube, and 10 mL of HPLC-grade acetonitrile was added. The mixture was vigorously shaken for one minute to ensure complete extraction of pesticide residues. A mixture of extraction salts consisting of 4g anhydrous magnesium sulfate ($MgSO_4$) and 1g sodium chloride (NaCl) was added immediately. The tube was shaken vigorously for another minute and centrifuged at 4,000 rpm for 5 minutes. For sample clean-up, 6 mL of the supernatant was transferred into a dispersive solid-

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phase extraction tube containing 150 mg primary secondary amine (PSA), 150 mg C18 sorbent, and 900 mg anhydrous magnesium sulfate. The mixture was vortexed for one minute and centrifuged again at 4,000 rpm for 5 minutes. The purified extract was filtered through a 0.22 µm PTFE syringe filter into HPLC sample vials before chromatographic analysis.

HPLC analysis

Pesticide residue analysis was carried out using a High-Performance Liquid Chromatography (HPLC) system equipped with a quaternary pump, autosampler, column oven, and diode-array detector (DAD). Separation was achieved using a reverse-phase C18 analytical column (250 mm × 4.6 mm, 5 µm particle size) maintained at 30°C. The mobile phase consisted of: Solvent A: ultrapure water containing 0.1% formic acid; Solvent B: HPLC-grade acetonitrile. Gradient elution was employed at a flow rate of 1.0 mL min^{-1} with an injection volume of 20 µL. The detector wavelength was optimised according to the pesticide standards analysed. Identification of pesticide residues was achieved by comparing retention times of sample peaks with those of certified analytical standards. Quantification was performed using external calibration curves prepared from mixed pesticide standards at different concentrations. Residue concentrations were expressed as mg kg^{-1} of dry weight.

Quality Assurance and Quality Control (QA/QC)

Quality assurance and quality control (QA/QC) procedures were implemented throughout sample preparation and instrumental analysis. Method blanks, laboratory duplicates, calibration verification standards, and recovery experiments were included during analysis. All samples were analysed in triplicate (R1–R3), and the results were expressed as the mean. Instrument calibration coefficients (R^2) exceeded 0.99 for all target pesticides, demonstrating acceptable analytical linearity.

Determination of exceedance factor

Unlike heavy metals, pesticides do not have natural geochemical background concentrations in soil or cereals because they are synthetic chemicals. Therefore, there are no universally accepted background values for these pesticides in soil or cereals. Regulatory agencies generally recommend using the Exceedance Factor (EF), a simple index used to determine how much a measured pesticide concentration exceeds the permissible limit (usually the MRL) [18].

The formula is:

$$\mathrm{EF}\,\frac{\text{measured concentration}}{\text{Maximum residue limit}}$$

EF Value	Interpretation
EF ≤ 1	Within permissible limit
EF > 1	Exceeds permissible limit
EF > 10	Extremely high contamination relative to MRL

Health risk assessment

The risk that pollution poses to humans can be estimated by using an efficient model called the human health risk model. Differences in physiology and behaviour of adults compared with children keep them separate. The study estimated the potential of non-carcinogenic and carcinogenic health risks for the two age groups.

Non- carcinogenic health risk assessment

The primary routes of exposure for children and adults to pesticide residues are through ingestion (ADI_{ing}), inhalation of suspended particles (ADI_{inh}), and dermal contact (ADI_{der}). Although dietary ingestion is the principal route of exposure for cereal consumers, additional exposure through dermal contact and inhalation of cereal dust may occur among individuals involved in grain handling, transportation, storage, processing, milling, packaging, and marketing. Consequently, all three exposure pathways were assessed to provide a more comprehensive evaluation of potential human exposure associated with cereal consumption and occupational handling. The non-carcinogenic health risk of a substance is determined by estimating the likelihood of adverse health effects at a specific dosage within a specific timeframe using the hazard quotient and hazard index. The hazard quotient (HQ) is referred to as the quotient of ADI divided by the chronic reference dose (RfD) of a certain pesticide residue in mg/kg/day. The potential hazard quotient (HQ) for each pesticide was calculated by using the following equation [19].

$$\mathrm{HQ}=\frac{ADI}{RfD}$$

If HQ < 1, it means that there are no adverse health consequences, whereas HQ > 1 suggests that there are probably harms [20].

The population's non-carcinogenic response to a certain number of pesticide residues is the total of all the HQs caused by each pesticide residue, known as the Hazard Index HI [21]. It was calculated using the equation below:

$$HI = \sum^{\mathrm{n}}{}_{\mathrm{i=1}}\left(\mathrm{HQ}\right)$$

The value of HI≤1 indicates that there is no significant risk of non-carcinogenic effects. On the other hand, there is a chance that non-carcinogenic effects may occur. When HI>1, the probability increases as the value of the HI increases [22].

Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics (Version XX) (or the statistical software actually used). Data are presented as mean ± standard deviation (SD) based on three independent replicate determinations (R1–R3). One-way analysis of variance (ANOVA) was used to evaluate differences in pesticide residue concentrations among cereal types. Where significant differences were observed, Tukey's Honestly Significant Difference (HSD) post hoc test was performed to identify pairwise differences between cereal groups. Statistical significance was established at $p < 0.05$.

For pesticides detected in only one cereal type or with insufficient observations across cereal groups, inferential

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statistical comparisons were not performed because the assumptions required for one-way ANOVA were not satisfied. Such pesticides were interpreted descriptively by reporting their occurrence, concentration levels, and compliance with established Maximum Residue Limits.

Results

F-rice =foreign rice, L-rice =local rice, E.high= extremely high, MRL= maximum residue limit, EF= exceedance factor.

Four pesticide residues, namely imidacloprid, acetamiprid, pendimethalin, and propiconazole, were detected in the analysed cereal samples. Mean residue concentrations ranged from 0.06 ± SD to 0.90 ± SD mg kg^{-1} (Table 1). Imidacloprid was the most frequently detected pesticide, occurring in beans, sorghum, local rice, maize, and wheat, whereas acetamiprid was detected only in beans and foreign rice. Pendimethalin was detected in sorghum, local rice, and maize, while propiconazole was detected exclusively in maize.

Comparison of the measured concentrations with their respective Maximum Residue Limits (MRLs) showed that all detected pesticide residues exceeded the recommended regulatory limits, with exceedance factor (EF) values ranging from 1.2 to 18.0. Pendimethalin exhibited the greatest level of contamination, recording the highest EF values in maize (18.0), local rice (17.2), and sorghum (17.0). Wheat contained the highest concentration of imidacloprid (0.73 mg kg^{-1}), corresponding to an EF of 14.6, whereas the lowest exceedance was observed for acetamiprid in beans (EF = 1.2) (Table 2).

One-way analysis of variance (ANOVA) indicated significant differences in imidacloprid concentrations among the cereal types (**$p < 0.05$**). Tukey's Honestly Significant Difference (HSD) post hoc test further revealed that wheat contained significantly higher imidacloprid concentrations than beans, sorghum, maize, and local rice ($p < 0.001$) (Table 2). However, no significant differences were observed among beans, sorghum, maize, and local rice ($p > 0.05$). Statistical comparison was not performed for acetamiprid, pendimethalin, and propiconazole because these pesticides were detected in too few cereal groups to satisfy the assumptions of one-way ANOVA (Table 3).

Following one-way analysis of variance (ANOVA), Tukey's Honestly Significant Difference (HSD) post hoc test was used to identify pairwise differences in pesticide residue concentrations among the cereal samples. The post hoc analysis was conducted only for pesticides that were detected in two or more cereal types with sufficient replicate measurements (R1–R3), as recommended for valid multiple-comparison procedures. For pesticides detected in only one cereal or not detected in the remaining cereals, statistical comparison was not performed because the assumptions required for ANOVA and Tukey's HSD were not met.

Tukey's HSD analysis for imidacloprid revealed that wheat contained significantly higher residue concentrations than beans, local rice, maize, and sorghum (adjusted $p < 0.001$) (Table 3). In contrast, no statistically significant differences were observed among beans, local rice, maize, and sorghum (adjusted $p > 0.05$), indicating that these cereals contained comparable levels of imidacloprid residues. For the remaining pesticides, including acetamiprid, pendimethalin and propiconazole, statistical multiple comparisons were not performed because these compounds were either absent or detected in only one cereal type. Consequently, there were insufficient comparable groups to satisfy the assumptions of one-way ANOVA and Tukey's HSD. These pesticides were therefore interpreted descriptively by reporting their occurrence, concentration ranges, and compliance with established maximum residue limits (MRLs) (Table 4).

Imidacloprid and acetamiprid were detected in beans at concentrations of 0.19 mg kg^{-1} and 0.06 mg kg^{-1}, respectively (Table 4). For both adults and children, Hazard Quotients (HQs) for ingestion, inhalation, and dermal exposure were all below the safety threshold of 1.0. The corresponding Hazard Indices (HIs) also remained below unity, indicating negligible cumulative non-carcinogenic health risks. Children

Table 1: Pesticide concentration, MRL, exceedance factor and exceedance status.

Sample	Pesticide	Concentration	mrl	ef	Status
Beans	Imidacloprid	0.19	0.05	3.8	Above
	Acetamiprid	0.06	0.05	1.2	Above
Sorghum	Imidacloprid	0.15	0.05	3.0	Above
	Pendimethalin	0.85	0.05	17	E.High
F-Rice	Acetamiprid	0.26	0.05	5.2	Above
L-Rice	Imidacloprid	0.12	0.05	2.4	Above
	Pendimethalin	0.86	0.05	17.2	E.High
Maize	Imidacloprid	0.18	0.05	3.6	Above
	Propiconazole	0.15	0.1	1.5	Above
	Pendimethalin	0.9	0.05	18	E.High
Wheat	Imidacloprid	0.73	0.05	14.6	E.High

F-rice =foreign rice, L-rice =local rice, E.high= extremely high, MRL= maximum residue limit, EF= exceedance factor.

Table 2: Analysis of variance for pesticides in contaminated cereals

Pesticide	Cereal	Mean (mg/kg)	MRL (mg/kg)	EF	ANOVA (p-value)	Tukey Group
Imidacloprid	Beans	0.19	0.05	3.8	<0.001	B
Imidacloprid	Wheat	0.73	0.05	14.6	<0.001	A

Table 3: Post Hoc Multiple Comparison of Pesticide Residues among Staple Cereals.

Comparison	Mean Difference	Adjusted p-value	Significant (p < 0.05)
Beans vs Local Rice	-0.022	0.0974	No
Beans vs Maize	-0.0037	0.9879	No
Beans vs Sorghum	-0.012	0.5515	No
Beans vs Wheat	0.1797	<0.001	Yes
Local Rice vs Maize	0.0183	0.1974	No
Local Rice vs Sorghum	0.01	0.6977	No
Local Rice vs Wheat	0.2017	<0.001	Yes
Maize vs Sorghum	-0.0083	0.8114	No
Maize vs Wheat	0.1833	<0.001	Yes
Sorghum vs Wheat	0.1917	<0.001	Yes

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consistently exhibited higher HQ and HI values than adults, reflecting their greater susceptibility to pesticide exposure (Table 5).

Similarly, Imidacloprid (0.15 mg kg^{-1}) and pendimethalin (0.85 mg kg^{-1}) were detected in sorghum (Table 5). Pendimethalin produced higher HQ and HI values than imidacloprid for both adults and children because of its higher residue concentration. Nevertheless, all HQ and HI values remained below the acceptable threshold (HQ and HI < 1), indicating negligible non-carcinogenic health risks. Among the evaluated exposure pathways, dermal exposure contributed more to total risk than ingestion and inhalation (Table 6).

Acetamiprid was the only pesticide detected in foreign rice, with a concentration of 0.26 mg kg^{-1} (Table 6). The calculated HQs for ingestion, inhalation, and dermal exposure were all below 1.0, resulting in cumulative HI values well within acceptable safety limits for both adults and children. These findings indicate that exposure to acetamiprid through the consumption and handling of foreign rice is unlikely to produce adverse non-carcinogenic health effects (Table 7).

LocAll rice contained imidacloprid (0.12 mg kg^{-1}) and pendimethalin (0.86 mg kg^{-1}) (Table 7). Pendimethalin generated higher HQ and HI values than imidacloprid in both age groups. However, all estimated HQ and HI values remained substantially below 1.0, indicating acceptable non-carcinogenic risk levels despite the observed exceedance of MRLs (Table 8).

Three Pesticides; imidacloprid (0.18 mg kg^{-1}), propiconazole (0.15 mg kg^{-1}), and pendimethalin (0.90 mg kg^{-1}) were detected in maize (Table 8). Propiconazole produced the highest cumulative HI, followed by pendimethalin and imidacloprid. Despite these differences, all HQ and HI values for both adults and children remained well below the USEPA safety threshold of 1.0, indicating negligible non-carcinogenic health risks (Table 9).

Imidacloprid was the only pesticide detected in wheat, with a concentration of 0.73 mg kg^{-1} (Table 9). Although wheat contained the highest imidacloprid concentration among all cereals analysed, the estimated HQs and cumulative HI values for adults and children remained below **1.0** for all exposure pathways. Children recorded slightly higher HI values than adults, but the estimated risks remained within acceptable limits, suggesting that current exposure levels are unlikely to cause adverse non-carcinogenic health effects.

Table 4: Hazard quotients and hazard index via ingestion, inhalation and dermal contact with pesticide accumulated in beans.

Sample	Age	Pesticide	Conc.	HQing	HQ inh	HQ der	HI
Beans	Adult	Imidacloprid	0.19	1.6E-08	6.302E-11	1.1E-05	1.141E-05
	Child			4.9E-08	1.241E-10	0.0007	0.0007467
	Adult	Acetamiprid	0.06	1.4E-08	5.528E-11	1E-05	1.027E-05
	Child			4.4E-08	1.117E-10	0.0006	0.00067

Table 5: Hazard quotients and hazard index via ingestion, inhalation and dermal contact with pesticide accumulated in Sorghum.

Sample	Age	Pesticide	Conc.	HQing	HQ inh	HQder	HI
Sorghum	Adult	Imidacloprid	0.15	1.4E-8	1.785E-10	9E-06	9.013E-06
	Child			4.3E-8	9.803E-11	0.0005	0.0005
	Adult	Pendimethalin	0.85	4.4E-8	2.184E-10	2.9E-5	2.911E-05
	Child			1.4E-7	3.166E-10	0.0019	0.0019

Table 6: Hazard quotients and hazard index via ingestion, inhalation and dermal contact with pesticide accumulated in foreign rice.

Sample	Age	Pesticide	Conc.	HQ ing	HQ inh	HQ der	HI
F-Rice	Adult	Acetamiprid	0.26	5.5E-08	1.120E-09	3.6E-05	3.562E-05
	children			1.7E-07	3.874E-10	0.0023	0.0023

Table 7: Hazard quotients and hazard index via ingestion, inhalation and dermal contact with pesticide accumulated in Local rice.

Sample	Age	Pesticide	Conc.	HQ ing	HQ inh	HQder	HI
L-Rice	Adult	Imidacloprid	0.12	1.1E-8	4.422E-11	7.2E-6	7.211E-06
	Child			3.5E-8	7.843E-11	0.0004	0.00047
	Adult	Pendimethalin	0.86	4.6E-8	1.806E-10	2.9E-5	2.945E-5
	Child			1.4E-7	3.203E-10	0.001	0.00192

Table 8: Hazard quotients and hazard index via ingestion, inhalation and dermal contact with pesticide accumulated in Maize.

Sample	Age	Pesticide	Conc.	HQing	HQ inh	HQder	HI
Maize	Adult	Imidacloprid	0.18	2.4E-8	6.634E-11	1.1E-5	1.082E-05
	Child			7.3E-8	1.176E-10	0.0007	0.0007
	Adult	Propiconazole	0.15	8.6E-8	2.424E-10	3.9E-5	3.954E-05
	Child			2.7E-7	4.298E-10	0.0025	0.00258
	Adult	Pendimethalin	0.9	6.7E-8	1.890E-10	3.1E-5	3.084E-05
	Child			2.1E-7	3.352E-10	0.002	0.002

Table 9: Hazard quotients and hazard index via ingestion, inhalation and dermal contact with pesticide accumulated in Wheat.

Sample	Age	Pesticide	Conc.	HQ ing	HQ inh	HQ der	HI
Wheat	Adult	Imidacloprid	0.73	5.3E-08	2.690E-10	4.4E-05	4.385E-05
	Child			1.6E-07	4.771E-10	0.00287	0.00286

Discussion

Occurrence and distribution of pesticide residues in staple cereals

The present study demonstrated the occurrence of four pesticide residues: imidacloprid, acetamiprid, pendimethalin, and propiconazole in staple cereals marketed in northern Nigeria. Their detection confirms the continued use of insecticides, herbicides, and fungicides during cereal production and post-harvest storage. Although only four of the targeted pesticides were detected, all positive samples contained residue concentrations exceeding their respective Maximum Residue Limits (MRLs), indicating non-compliance with recommended pesticide application practices and raising concerns regarding food safety. Similar findings have been reported in several developing countries where inappropriate pesticide application, poor adherence to pre-harvest intervals,

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and inadequate storage management have resulted in elevated pesticide residues in cereal grains [23-25].

Imidacloprid was the most frequently detected pesticide, occurring in beans, sorghum, local rice, maize, and wheat. This widespread occurrence is consistent with its extensive use as a systemic neonicotinoid insecticide for controlling sucking and chewing insect pests in cereal production. Its persistence in harvested grains may be attributed to repeated applications during crop cultivation, seed treatment, and storage, coupled with its relatively high stability under certain environmental conditions. Similar observations have been reported in China, Iran, and several African countries, where imidacloprid was among the most frequently detected pesticide residues in cereal commodities because of its broad-spectrum activity and widespread agricultural use [25,24].

Pendimethalin exhibited the highest residue concentrations and exceedance factors, particularly in maize, local rice, and sorghum. As a pre-emergence herbicide widely used for weed control, pendimethalin may persist in agricultural soils and be absorbed by crops under intensive cultivation systems. Elevated residue levels may therefore reflect repeated herbicide application, poor compliance with recommended application rates, or failure to observe appropriate pre-harvest intervals. Similar persistence of pendimethalin in cereals has been reported in international monitoring studies, where inappropriate herbicide management contributed to residue concentrations above established regulatory limits [26,27].

Acetamiprid and propiconazole showed more limited distributions, being detected in relatively few cereal types. This pattern probably reflects differences in crop-specific pesticide registration, pest pressure, agronomic practices, and disease management strategies. Propiconazole, for example, was detected only in maize, suggesting that fungicide application may have been targeted at fungal diseases specific to maize production or storage. Likewise, acetamiprid was detected only in beans and foreign rice, indicating selective application against insect pests affecting these commodities. Comparable crop-specific distribution patterns have been reported in studies from Nigeria and other countries, where the occurrence of individual pesticide residues depended largely on crop management practices and regional pesticide usage patterns [28,29].

The statistical analysis further demonstrated significant variation in imidacloprid concentrations among cereal types. Wheat contained significantly higher imidacloprid residues than beans, sorghum, maize, and local rice (Tukey's HSD, $p < 0.001$), whereas no significant differences were observed among the remaining cereal types. The elevated concentration observed in wheat may reflect differences in pesticide application frequency, storage duration, environmental conditions, or residue retention characteristics of wheat grains. In contrast, statistical comparisons were not performed for acetamiprid, pendimethalin, and propiconazole because these pesticides were detected in too few cereal groups to satisfy the assumptions required for one-way ANOVA. This analytical approach ensures that statistical conclusions are based on appropriate and valid comparisons.

Pesticide residues in beans

Among the exposure pathways evaluated, ingestion contributed the highest proportion of the total risk, while inhalation contributed the least. This finding is expected because dietary intake is recognised as the primary route of human exposure to pesticide residues in contaminated food and environmental media [30]. Similar observations were reported by Li *et al.* [25], who found that ingestion was the dominant pathway contributing to pesticide exposure among consumers of agricultural products in China.

Children consistently recorded higher HQ and HI values than adults for all pesticides investigated. This trend can be attributed to children's lower body weight, higher food consumption rate per unit body mass, increased hand-to-mouth behaviour, and developing physiological systems, which make them more susceptible to environmental contaminants [18]. Similar findings were reported by Akoto *et al.* [31] in Ghana and Oladapo *et al.* [11] in Nigeria, where children exhibited greater pesticide exposure risks than adults despite having comparable residue concentrations.

Imidacloprid and acetamiprid detected in beans generated extremely low HQ and HI values. These pesticides belong to the neonicotinoid group, which generally exhibits lower mammalian toxicity than many conventional organophosphate pesticides [32]. The low risk estimates observed in this study may be due to the comparatively low residue concentrations detected in the grain samples. Nevertheless, prolonged exposure to neonicotinoids has been associated with neurological and developmental effects, particularly in vulnerable populations, emphasising the importance of continuous monitoring [33].

Pesticides residues in sorghum

Pendimethalin recorded the highest HI value among the pesticides detected in sorghum. This observation is likely associated with its relatively high residue concentration in the grain sample. Pendimethalin is widely used as a pre-emergence herbicide and has been reported to persist in agricultural soils and crops following repeated application [34]. However, despite its comparatively higher contribution to total risk, the resulting HI values remained well below the threshold value of 1, suggesting that the detected concentrations are unlikely to cause adverse health effects.

The findings of this study agree with those reported by Oladapo *et al.* [11], who evaluated pesticide residues in cereals sold in southwestern Nigeria and found that most pesticides produced HQ values below unity, indicating acceptable health risks. Similarly, Akinneye *et al.* [35] reported low non-carcinogenic risks associated with pesticide residues in food crops consumed in Lagos State, Nigeria.

However, the present findings differ from those reported by Agbu and Shingu [36], who observed HQ values exceeding 1 for several pesticides detected in cereals cultivated in Wukari, Nigeria. The authors attributed the elevated risk levels to excessive pesticide application, poor compliance with recommended pre-harvest intervals, and inadequate

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regulatory control. Li *et al.* [25] reported HQ and HI values below 1 for most pesticide residues detected in medicinal plants in China, concluding that the products posed minimal health risks to consumers. Likewise, Heshmati and colleagues [24] found low dietary risks associated with pesticide residues in cereals consumed in Iran.

Pesticides residues in foreign rice

The low risk estimates observed for acetamiprid in foreign rice may be attributed to the relatively low concentration detected and the comparatively low mammalian toxicity of neonicotinoid insecticides. Acetamiprid belongs to the neonicotinoid class, which was developed as a safer alternative to many conventional organophosphate and carbamate pesticides due to its selective toxicity towards insects [32]. Despite the low risk estimates obtained in this study, long-term exposure to neonicotinoids has been associated with neurological, developmental, and endocrine disturbances, necessitating continuous monitoring of residue levels in food commodities [33].

Pesticide residues in local rice

In local rice, pendimethalin generated higher HQ and HI values than imidacloprid. This finding may be related to the higher concentration of pendimethalin detected in the sample and its environmental persistence. Pendimethalin is a pre-emergence herbicide known for its strong adsorption to soil particles and relatively slow degradation under field conditions, characteristics that can promote residue persistence and crop uptake [34]. Nevertheless, the resulting risk estimates remained substantially below unity, indicating that the detected residue levels do not constitute an immediate health concern. However, the results differ from those reported by Sosan *et al.* [28], who observed elevated pesticide residue concentrations and corresponding health risks in selected food commodities in Nigeria. Such differences may be due to variations in pesticide usage patterns, environmental conditions, crop management practices, and adherence to recommended pre-harvest intervals. Excessive pesticide application and poor regulatory compliance have been identified as major causes of elevated residue levels in developing countries [4].

Pesticides residues in maize

The higher HI values observed for propiconazole in maize compared to other pesticides may be explained by the fungicide's persistence and frequent use in cereal cultivation. Propiconazole belongs to the triazole class of fungicides and is widely applied for the management of fungal diseases in grains. Previous studies have shown that repeated applications can lead to residue accumulation in agricultural soils and crops [27]. However, despite generating the highest risk estimate among the maize pesticides, the calculated HI remained far below the acceptable threshold, suggesting minimal non-carcinogenic risk.

Pesticides residues in wheat

The relatively low risk estimates observed despite the presence of measurable imidacloprid residues may be attributed to the low daily exposure doses obtained from the various exposure pathways and the relatively high reference dose used in risk characterisation. Imidacloprid is a neonicotinoid insecticide widely used in cereal production because of its effectiveness against sucking and chewing insect pests. The compound exhibits selective toxicity toward insects and generally lower toxicity to mammals compared with many conventional insecticides such as organophosphates and carbamates [32]. This characteristic may partly explain the low HQ and HI values obtained in the present study.

Among the evaluated pathways, dermal exposure contributed more to the overall risk than ingestion and inhalation. This observation may be related to the exposure assumptions used in the risk assessment model, particularly skin adherence factors and dermal absorption parameters. However, inhalation exposure contributed negligibly to the overall risk because imidacloprid has low volatility and limited potential for atmospheric dispersion under normal environmental conditions [37]. Similar findings have been reported in pesticide exposure studies where inhalation was the least significant contributor to total exposure [25].

Children exhibited slightly higher HQ and HI values than adults, which is consistent with previous risk assessment studies. This increased susceptibility is attributed to children's lower body weight, higher food consumption rate per unit body mass, and developing physiological systems that may be more sensitive to chemical exposure [18]. Akoto *et al.* [31] similarly reported higher pesticide exposure risks among children than adults in a dietary risk assessment study conducted in Ghana. Likewise, Oladapo *et al.* [11] observed that children represented the most vulnerable population group in the assessment of pesticide residues in cereals marketed in Nigeria.

The findings of the present study are consistent with several investigations conducted within and outside Nigeria. Akinneye *et al.* [35] reported HQ values below 1 for most pesticide residues detected in commonly consumed food crops in Nigeria, indicating negligible non-carcinogenic risks. Similarly, Oladapo *et al.* [11] found that pesticide residues detected in cereal grains marketed in southwestern Nigeria did not pose significant health risks to consumers. These studies support the conclusion that pesticide residues frequently detected in food commodities may remain within concentrations that are considered safe for human exposure.

Internationally, Li *et al.* [25] reported low non-carcinogenic health risks associated with pesticide residues in agricultural products from China, while Heshmati *et al.* [24,38,39,40,41] found that pesticide residues detected in cereals consumed in Iran produced HQ and HI values below unity. The agreement between these studies and the present findings suggests that the residue level of imidacloprid detected in wheat falls within a range that is unlikely to result in adverse health outcomes.

Conclusion

This study demonstrated the occurrence of pesticide residues in commonly consumed cereals marketed in northern Nigeria.

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Four pesticides, imidacloprid, acetamiprid, pendimethalin, and propiconazole, were detected at concentrations ranging from 0.06 to 0.90 mg kg^{-1}. All detected residues exceeded their respective maximum residue limits, with exceedance factors ranging from 1.2 to 18.0, indicating widespread non-compliance with recommended pesticide residue standards. Pendimethalin was the predominant contaminant and recorded the highest residue levels in maize, sorghum, and local rice. One-way analysis of variance (ANOVA) indicated significant differences in imidacloprid concentrations among the cereal types (**$p < 0.05$**). Tukey's Honestly Significant Difference (HSD) post hoc test further revealed that wheat contained significantly higher imidacloprid concentrations than beans, sorghum, maize, and local rice (**$p < 0.001$**). Despite the observed exceedance of regulatory limits, the estimated hazard quotients and hazard indices for ingestion, inhalation, and dermal exposure remained below the acceptable threshold ($HI < 1$) for both adults and children, suggesting that current exposure levels are unlikely to produce significant non-carcinogenic health effects. Nevertheless, children consistently exhibited higher exposure estimates than adults, highlighting their greater vulnerability. The persistence of pesticide residues above permissible limits emphasises the need for strengthened pesticide regulation, improved farmer education on good agricultural practices, compliance with pre-harvest intervals, and routine residue surveillance. Continuous monitoring is essential to safeguard food quality, minimise chronic dietary exposure, and protect consumer health.

Author's contribution

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Data availability

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

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