



Quantification of pesticide residues in cucumbers and watermelons from Dar es Salaam city markets and assessment of associated non-carcinogenic dietary health risks

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ABSTRACT

The application of pesticides improves crop productivity and quality by controlling insect pests. However, their excessive use negatively affects human health. The present study quantified pesticide residues in cucumber ($n = 25$) and watermelon ($n = 25$) from five Dar es Salaam city markets using the Quick, Easy, Cheap, Effective, Rugged, and Safe (QuEChERS) multi-residue extraction method coupled with Liquid Chromatography—Tandem Mass Spectrometry (LC-MS/MS) and assessed associated dietary health risks. Twenty-three pesticides were detected; MRL exceedances occurred in 70% of cucumber samples and 85% of watermelon samples, with carbendazim and hexaconazole being the most prevalent. The World Health Organisation classified 78% of detected pesticides as moderately to severely hazardous (Classes Ib, II, and III). Whilst adult hazard index (HI) values were below 100% (acceptable risk), children exhibited critical HI exceedances: lufenuron (682.1%) and carbendazim (137.4%) in cucumber, and acetamiprid (158.2%) in watermelon. The cumulative hazard index (HI) for cucumber samples was 1419.8% and 401.2% for children and adults, respectively; for watermelon samples, the cumulative HI was 672.7% for children and 150.3% for adults. These findings highlight urgent gaps in pesticide regulation, enforcement, and farm-level practices in Tanzania that warrant immediate attention from policy-makers and stakeholders to inform effective interventions and safeguard public health.

1. Introduction

Plant-based foods, particularly fruits and vegetables (F&V) such as cucumber and watermelon, are essential components of the human diet, providing key sources of minerals, dietary fibre, vitamins, and phytochemicals that contribute to health and nutritional well-being (Nadeem et al., 2022; Mallick, 2022). A joint report by the World Health Organisation (WHO) and Food and Agriculture Organisation (FAO) recommends a minimum daily intake of 400 g of F&V (excluding tubers) to reduce the risk of chronic non-communicable diseases, including cancer, obesity, diabetes, cardiovascular disease, and stroke (FAO and the Ministry of Social Development and Family of Chile., 2021). Despite these well-established health benefits, evidence from various studies indicates that consuming certain F&V, including cucumber and watermelon, may lead to a comparatively higher dietary intake of pesticide

residues (PRs) than those in other food and beverage groups. This is largely because these commodities are typically consumed raw or minimally processed, thereby limiting opportunities to remove or degrade residues prior to consumption (Beyuo et al., 2024; Wahab et al., 2022).

Pesticides are widely used in agriculture to control pests, diseases, and weeds, thereby enhancing crop yield and quality (Si et al., 2021). Based on their mode of action, pesticides are broadly categorised as systemic and non-systemic. Systemic pesticides penetrate plant tissues, including leaves, fruits, and rhizomes, by osmosis, making their complete removal through conventional washing or processing particularly challenging (Garud et al., 2024). Global pesticide use has increased rapidly in recent decades, driven by the expansion of cultivated land, rising pest resistance, and the intensification of crop production systems. In addition, ongoing climate change is intensifying pest pressure and

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crop vulnerability, thereby further increasing pesticide use (Zhang, 2018). Commonly used pesticide groups in horticultural systems include organophosphates, carbamates, and neonicotinoids, many of which function as broad-spectrum insecticides, fungicides, or herbicides and are registered for use across diverse crops (Qin et al., 2021). In Tanzania, several neurotoxic pesticide categories, including organophosphates, carbamates, and neonicotinoids, are registered for agricultural use, and their use has increased alongside the growing demand for cucumber and watermelon (Ngowi, 2002).

In addition, pesticide residues (PRs) in F&V pose direct health risks. Chronic dietary exposure resulting from the use of pesticides has been associated with a wide range of adverse health effects, including neurodevelopmental issues (Botnaru et al., 2025; Popescu et al., 2025), endocrine disruption (Coppola et al., 2025; El-Sheikh et al., 2022; Magdaleno-Magniales et al., 2025), carcinogenicity (Eissa et al., 2024; Sivaperumal et al., 2022; Park et al., 2022; Khoshnam et al., 2022), colorectal, prostate, and breast cancer risk (Cavalier et al., 2023; Ghimire et al., 2025; Rebouillat et al., 2021), hepatotoxicity (Chai et al., 2022; Si et al., 2025), reproductive dysfunction (Beyuo et al., 2024; Kazemi et al., 2025; Kurniyawan et al., 2024), and various genetic and metabolic disorders in humans (Hood et al., 2022). Other adverse health effects of PRs' ingestion include headache, nausea, and blindness (Beyuo et al., 2024). In recognition of these risks, the Codex Alimentarius Commission (CAC) has, as of 2024, established 6453 maximum residue limits for various pesticide—commodity combinations, including those applicable to cucumber and watermelon, to guide international regulatory frameworks. While chronic dietary exposure to pesticide residues has been linked to both carcinogenic and non-carcinogenic health outcomes, the present study deliberately focuses on assessing non-carcinogenic risks. The majority of pesticides registered for use on cucurbits in Tanzania exert their primary toxicological effects via non-carcinogenic mechanisms, including acetylcholinesterase inhibition, neurotoxicity, and endocrine disruption, rather than through carcinogenic pathways (WHO, 2021).

In Tanzania, pesticide use is regulated by the Tanzania Plant Health and Pesticides Authority (TPHPA). However, the application of synthetic pesticides in horticultural production has increased markedly since the adoption of a trade liberalisation policy in 1992, which led to the withdrawal of government subsidies for agricultural inputs and facilitated the importation and distribution of agrochemicals through private dealers, thereby significantly expanding farmers' access to pesticides (Bee et al., 1997). This trend is particularly evident in the cultivation of watermelon and cucumber, which are widely consumed nationwide and hold considerable nutritional and economic importance (Mengistie et al., 2017). Despite the widespread use of pesticides in cucurbit production in Tanzania, limited empirical data exist on the nature and magnitude of pesticide residues in commonly consumed fresh produce such as cucumber and watermelon, particularly within major urban supply chains. Furthermore, no previous study has systematically evaluated the associated chronic dietary health risks for consumers in Dar es Salaam city, Tanzania. Therefore, this study aimed to quantify pesticide residues in cucumber and watermelon from five major markets in Dar es Salaam, Tanzania, and to assess the associated dietary health risks. The findings are intended to address a significant knowledge gap by generating locally relevant data that may inform policymakers, risk managers, and regulatory institutions, including the Tanzania Bureau of Standards (TBS) and the Tanzania Plant Health and Pesticides Authority (TPHPA), in their ongoing efforts to strengthen pesticide residue monitoring, enforcement, and compliance systems in the country.

2. Materials and methods

2.1. Study area

This study was conducted in five purposively selected markets,

namely Kisutu, Ilala, Mabibo, Veterinary, and Buguruni, located within Dar es Salaam city (Fig. 1), which is the largest and a promising area for sustainable development along Tanzania's Indian Ocean coastline. The city is located between latitudes $-6^{\circ}49'24.56''$ and longitude $39^{\circ}16'10.24''$ East. It is also an important hub for horticultural products, sourcing supplies from peri-urban and rural agricultural areas, including the Pwani Region. Its large population and vibrant market system make it a key location for evaluating food safety issues associated with fresh produce consumption.

2.2. Study design

A descriptive cross-sectional study design was used to quantify pesticide residues in cucumber and watermelon samples and to assess their associated dietary health risks. This design was considered suitable for characterising the prevalence and concentration of pesticide residues in food commodities at a given point in time across several sampling locations. Analyses for pesticide residues were conducted at the Tanzania Plant Health and Pesticides Authority (TPHPA) laboratory in Arusha, Tanzania, which holds accreditation to ISO/IEC 17025:2017, the international standard for testing and calibration laboratory management systems, thereby guaranteeing the reliability and traceability of analytical results.

2.3. Chemicals and reagents

Pesticides with certified reference standards representing insecticides, fungicides, and herbicides with purities ranging from 97% to 98% were purchased from an accredited supplier, AnalytiChem Belgium NV, previously known as Chem-Lab NV. Analytical-grade formic acid and ammonium formate were also purchased from AnalytiChem Belgium NV and used to prepare the mobile phase. QuEChERS extraction salts consisting of anhydrous magnesium sulphate (MgSO_4) and sodium acetate (NaOAc), as well as clean-up sorbents including primary and secondary amine (PSA) and graphitised carbon black (GCB), were used for sample preparation. Individual stock solutions were prepared in acetonitrile and further diluted to prepare mixed working standards.

2.4. Sample collection and storage

A total of 50 fresh produce samples were randomly collected between late December 2025 and early January 2026 from five purposively selected markets in Dar es Salaam city for pesticide residue analysis. The samples comprised 25 cucumber (vegetable) and 25 watermelon (fruit) samples, representing commonly consumed fresh commodities in the city. Sample collection was conducted in accordance with the principles and procedures outlined in the European Commission Directive 2002/63/EC for the official control of pesticide residues in plant-origin food products. Each sample (1–2 kg) was placed in a clean polyethylene bag to prevent cross-contamination and deterioration, then sealed and labelled with a unique sample identification code. Samples were then transported to the laboratory under chilled conditions and stored at 4°C until further processing. Sample packaging and storage procedures were conducted in accordance with European Union SANTE 11312/2021 guidelines for pesticide residue analysis.

2.5. Sample preparation

Sample preparation was conducted in two phases: initial homogenisation in the Food Science and Technology laboratory at the University of Dar es Salaam, followed by extraction and analysis at the TPHPA laboratory in Arusha. A representative portion of each sample, weighing between 600 g and 1 kg, was chopped into small pieces ($1-2\text{ cm}^3$) and homogenised for five minutes using a fruit and vegetable pulper (model HM-20L; Sanda Industrial Co., Ltd., Xi'an, China), following a procedure adapted from ISO 874:1980. From the resulting homogenate, 200 g was

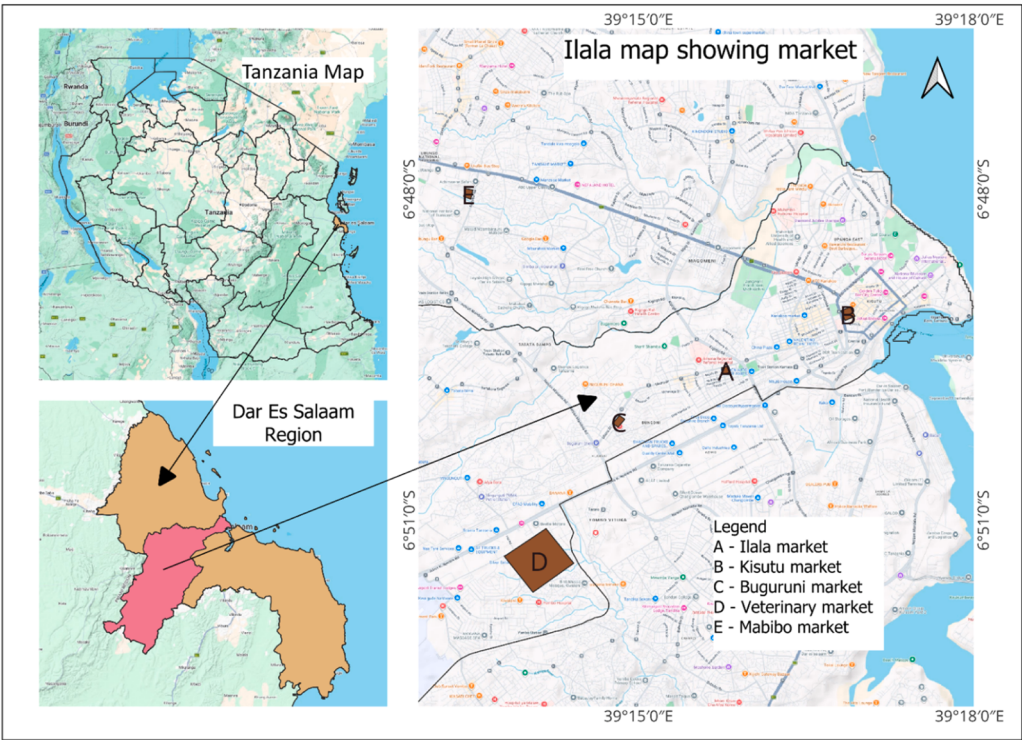


Fig. 1. Maps showing the sampling locations (markets): Source (Author construction, 2026).

transferred into a pre-labelled plastic bottle, sealed, placed in an ice-cooled box (maintained at approximately 4 °C), and transported within 10 h to the TPHPA laboratory in Arusha to minimise enzymatic degradation and chemical hydrolysis of pesticide residues. Upon arrival, samples were immediately transferred to a freezer and stored at –18 °C until extraction and LC-MS/MS analysis, all of which were completed within 14 days of collection to ensure residue stability.

2.6. Sample extraction and purification

Extraction and purification were performed using a buffered QuEChERS procedure adapted from EN 15662. A total of 10 mL of acetonitrile (ACN) was added to a 10 g homogenised sample in a 50 mL centrifuge tube, followed by the addition of an internal standard (ISTD) and subsequent shaking. Subsequently, 4 g of anhydrous MgSO₄, 1 g of NaCl, 1 g of Na₂Citrate·2 H₂O, and 0.5 g of Na₂HCitrate·1.5H₂O were added. The tube was then vigorously shaken for 1 min and centrifuged at 3000 rpm for 5 min, after which the supernatant was carefully removed for purification. Purification was performed using dispersive solid-phase extraction (d-SPE). A 1.0 mL aliquot of the extract supernatant was added to a d-SPE centrifuge tube containing 25 mg of primary and secondary amine (PSA) and 150 mg of anhydrous MgSO₄. To enhance matrix cleanup, 7.5 mg of graphitised carbon black (GCB) was added to remove co-extracted pigments and sugars efficiently. The mixture was vortexed for 1 min and centrifuged at 3000 rpm for 5 min, after which the resulting supernatant was carefully collected and passed through a 0.22 µm polytetrafluoroethylene (PTFE) syringe filter to remove any residual particulate matter. The filtered extract was then transferred into an autosampler vial and subjected to LC-MS/MS analysis.

2.7. Residue analysis

2.7.1. LC-MS/MS conditions

Pesticide residues were determined by Liquid Chromatography–Tandem Mass Spectrometry (LC-MS/MS) following the EN 15662:2018 QuEChERS method for foods of plant origin.

Analysis was performed using a Thermo Scientific Vanquish Flex Binary UHPLC coupled to a TSQ Quantis triple-quadrupole mass spectrometer equipped with a heated electrospray ionisation (H-ESI II) source. Chromatographic separation was achieved on a C18 column (100 mm × 2.1 mm internal diameter, 2.6 µm particle size) maintained at 35 °C, with the autosampler at 10 °C and an injection volume of 10 µL. The gradient elution was performed using two mobile phases. The mobile phases consisted of (A) 5 mM ammonium formate with 0.1% formic acid in water: methanol (98:2, v/v) and (B) 5 mM ammonium formate with 0.1% formic acid in methanol: water (98:2, v/v). The flow rate was maintained at 0.3 mL min^{–1} using the gradient programme detailed in Table 1, with a total run time of 12.5 min.

The mass spectrometer was operated in timed selected reaction monitoring (t-SRM) mode under both positive and negative ionisation. In conventional SRM, all transitions are continuously monitored throughout the chromatographic run, thereby increasing background noise and reducing sensitivity. In contrast, t-SRM allows each transition to be monitored only within a narrow time window (typically ±30–60 s) centred on the analyte's expected retention time. This approach significantly reduces spectral noise, enhances signal-to-noise ratios, and improves overall method sensitivity, which is particularly advantageous for multi-residue pesticide analysis where dozens of analytes are monitored simultaneously. The t-SRM windows were optimised for each analyte based on its empirically determined retention time from

Table 1
Gradient program for LC-MS/MS analysis.

Time (min)	Phase A%	Phase B%	Flow (mL/min)
0.000	98	2	0.300
1.000	98	2	0.300
2.000	50	50	0.300
9.000	2	98	0.300
10.000	2	98	0.300
11.000	50	50	0.300
12.000	98	2	0.300
12.500	Stop Run		

standard injections. Spray voltages were set to 4000 V (positive) and 2750 V (negative), sheath gas to 30 arb, auxiliary gas to 6 arb, ion transfer tube temperature to 325 °C, and vaporiser temperature to 350 °C. Quantification was performed using matrix-matched calibration curves prepared at eight concentration levels (1.562–200 µg/kg). Pesticide identification and confirmation were based on matching retention times and relative ion intensities (ion ratios) with those of calibration standards within the tolerances defined by EN 15662:2018.

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2.7.2. Method validation

A full method validation was conducted separately for cucumber and watermelon matrices in accordance with EN 15662:2018 and SANTE/11312/2021 guidelines. The following validation parameters were evaluated for each pesticide residue in each matrix.

2.7.2.1. Selectivity. Selectivity was assessed by analysing five independent blank cucumber and watermelon samples (previously confirmed to be free of target analytes) to detect interfering peaks at the retention times of each pesticide residue. No interfering peaks exceeding 30% of the LOQ signal were observed for any analyte in either matrix, confirming method selectivity.

2.7.2.2. Linearity and calibration range. Matrix-matched calibration curves were prepared by spiking blank cucumber and watermelon extracts with mixed pesticide standards at eight concentration levels: 1.562, 3.125, 6.25, 12.5, 25, 50, 100, and 200 µg/kg. Each calibration level was analysed in triplicate. Linearity was evaluated using the coefficient of determination (R^2) from linear regression analysis with $1/x$ weighting. All analytes exhibited $R^2 \geq 0.99$ in both matrices, indicating excellent linearity across the tested concentration range.

2.7.2.3. Accuracy (recovery). Accuracy was determined by spiking blank cucumber and watermelon samples at two concentrations: 10 µg/kg and 100 µg/kg ($n = 6$ per level). Spiked samples were processed through the entire QuEChERS extraction and purification procedure prior to LC-MS/MS analysis. Recovery (%) was calculated as (measured concentration / spiked concentration) $\times 100$. Acceptable recovery was defined as 70–120% in accordance with the SANTE/11312/2021 guidelines.

2.7.2.4. Precision (repeatability). Precision was evaluated as repeatability (intra-day) by analysing six replicate spiked samples at 100 µg/kg on the same day under the same operating conditions. The relative standard deviation (RSD%) was calculated as (standard deviation/

mean) $\times 100$. Acceptable precision was defined as $RSD \leq 20\%$. All analytes in both matrices met this criterion.

2.7.2.5. Limits of detection and quantification. The limit of detection (LOD) was determined as the lowest analyte concentration that produced a signal-to-noise (S/N) ratio of 3:1, based on the analysis of spiked samples. The limit of quantification (LOQ) was determined as the lowest concentration yielding an S/N ratio of 10:1, with acceptable recovery (70–120%) and precision ($RSD \leq 20\%$). For analytes for which the lowest calibration level (1.562 µg/kg) met these criteria, that value was adopted as the LOQ.

2.7.2.6. Matrix effect. Matrix effects (ME) were evaluated by comparing the slope of the matrix-matched calibration curve with that of the solvent-only calibration curve, calculated as $ME (\%) = [(slope \text{ matrix}/slope \text{ solvent}) - 1] \times 100$. Positive values indicate ion enhancement, whilst negative values indicate ion suppression. $|ME| < 20\%$ was considered negligible, 20–50% moderate, and $> 50\%$ strong. Matrix-matched calibration was used for all quantitative analyses to compensate for observed matrix effects.

2.7.2.7. Carryover. Carryover was assessed by injecting a blank solvent sample immediately after the highest calibration standard (200 µg/kg). Carryover was considered acceptable if the response in the blank was $\leq 20\%$ of the LOQ response for each analyte. No significant carryover was observed for any analyte in either matrix.

2.7.2.8. Stability. Stock standard stability was verified by comparing fresh and six-month-old standard solutions (stored at -20°C), with differences $< 15\%$ considered acceptable. Processed sample stability in the autosampler (10°C) was confirmed for 48 h, with all analytes showing $< 20\%$ deviation from the initial response. Freeze–thaw stability (-18°C to room temperature, three cycles) was also confirmed for all analytes ($< 20\%$ deviation).

2.8. Health risk assessment

Dietary health risk assessment for consumers resulting from the consumption of pesticide-contaminated cucumber and watermelon was conducted in accordance with EFSA (2019) and WHO (2021) guidelines, using the hazard index (HI) as the primary risk characterisation metric, calculated as shown in Eq. 1:

$$HI = EDI/ADI \times 100 \quad (1)$$

where EDI denotes the estimated daily intake (in mg/kg body weight), and ADI denotes the acceptable daily intake (ADI in mg/kg body weight). ADI values for all detected pesticides were sourced from the EU Pesticides Database. The EDI for each pesticide was calculated using Eq. 2:

$$EDI = C \times B/W \quad (2)$$

Where C represents the pesticide residue concentration in the sample (mg/kg), B denotes the average daily fruit and vegetable consumption per person, estimated at 162 g (0.162 kg) per person per day in Dar Es Salaam city based on the Tanzania National Bureau of Statistics Report of 2024. W signifies the mean body weight (kg). Adult body weight was estimated at 60 kg, while children aged 2–5 years were assigned a body weight of 16.7 kg. Risk assessment was performed separately for adults and children under 6 years of age. Although body weight estimates differ between children aged 6–9 and 10–12 years, this study used the weight of children aged 2–5 years, who are lighter, thereby increasing their exposure risk. Risk assessments were conducted separately for adults and children for each detected pesticide residue. Food is considered safe for consumption when $HI \leq 100\%$; an $HI > 100\%$ indicates an unac-

ceptable chronic dietary risk to the consumer (Akoto et al., 2016).

2.9. Cumulative hazard index

In addition to individual pesticide risk assessment, cumulative dietary exposure was evaluated to account for the frequent co-occurrence of multiple pesticide residues within single samples. The cumulative Hazard Index (HI-cumulative) was calculated as the sum of individual hazard indices for all pesticides detected in each sample, as shown in Eq. 3:

$$HI_{cumulative} = \sum EDI/ADIX100 \quad (3)$$

The present approach assumed dose addition, which is considered appropriate for screening-level cumulative risk assessments when specific mechanism-of-action data are unavailable. A cumulative HI value $\leq 100\%$ was considered to indicate no significant cumulative risk to human health, whilst values exceeding 100% were interpreted as indicative of unacceptable cumulative dietary exposure risk. For pesticides without established ADI values, including acephate and dimethoate, these residues were excluded from the cumulative HI calculation, as their health-based reference values are unavailable. This represents a recognised conservative limitation of the cumulative risk assessment.

Pesticide residue concentrations were assessed against MRLs established by the CAC and the European Union (EU) under Regulation (EC) No 396/2005 and its subsequent amendments. However, it is important to note that Codex MRLs for several pesticide compounds examined in this study were set prior to recent toxicological reevaluations and have not been revised to align with current risk assessment frameworks. Additionally, for some compounds, MRL data were unavailable in the Codex database. Consequently, EU MRLs were used as the primary reference standard in this assessment due to their broader coverage and alignment with contemporary regulatory standards and risk assessment methodologies.

2.10. Data analysis

The data analysis was conducted using Microsoft Excel version 2022 (Microsoft Corp, Redmond, USA). Descriptive statistics, including the mean, minimum and maximum residue levels of pesticide for each crop, were calculated for all detected pesticide compounds. The residue levels were then compared with the respective EU MRLs for each pesticide-crop combination to assess compliance and potential safety concerns.

3. Results and discussion

3.1. Pesticide residue concentrations in cucumber

The data presented in Table 2 reveal that cucumber samples frequently contain pesticide residues exceeding established MRLs, indicating widespread contamination and non-compliance across various markets. This pattern suggests extensive pesticide application in cucumber cultivation within the region. However, it is important to note that residue levels are influenced by multiple factors, including application rates, pre-harvest intervals, and environmental factors, and do not directly measure use intensity, given that the majority of the produce sold in the sampled markets originated from the Pwani Region, rather than from market-specific factors or post-harvest handling. The utilisation of the t-SRM mode in analysis facilitated the reliable identification and quantification of 23 pesticide compounds in all samples. This mode minimised background interference and yielded clean chromatographic peaks with high signal-to-noise ratios, ensuring confidence in the analytical results.

The analysis identified some samples with notably high pesticide residues, specifically dimethoate (27.367 mg/kg) and lufenuron

(34.65 mg/kg). These results are supported by clear chromatographic peaks and accurate ion ratios, as shown in Supplementary Figures. However, since these concentrations are near or above the calibration curve's upper limit (200 µg/kg after dilution), they should be interpreted with caution due to potential quantification uncertainties at these levels. Importantly, sensitivity analysis excluding the top 5% of extreme values still revealed unacceptable health risks for children, indicating that the overall conclusion about the public health threat remains robust despite these high outliers.

Acephate was detected at significantly elevated concentrations across samples, with mean concentrations ranging from 2.917 to 6.333 mg/kg, far exceeding the established MRL of 0.01 mg/kg. Similarly, lufenuron was identified at significantly high residue levels, with mean concentrations ranging from 7.635 to 15.983 mg/kg and maximum values reaching 34.653 mg/kg, suggesting substantial non-compliance with recommended doses and pre-harvest intervals. The neonicotinoid insecticides (imidacloprid and acetamiprid) were routinely detected at concentrations exceeding regulatory thresholds, with imidacloprid exhibiting mean concentrations of 1.957–6.034 mg/kg against an MRL of 0.5 mg/kg, and acetamiprid ranging from 0.247 to 1.710 mg/kg, exceeding the MRL of 0.05 mg/kg in most samples. On the other hand, thiamethoxam was detected at relatively lower concentrations (0.089–0.155 mg/kg), all below its MRL of 0.5 mg/kg.

Among organophosphate insecticides, dimethoate showed significant variability and frequent exceedances, with mean concentrations ranging from 0.175 to 6.023 mg/kg and maximum levels reaching 27.367 mg/kg, well above the MRL of 0.01 mg/kg. These findings indicate inconsistent application practices and raise serious concerns about chronic dietary exposure. Among fungicides, carbendazim, hexaconazole, cyproconazole, triadimefon, and triadimenol were consistently detected at concentrations exceeding their respective MRLs in all samples. Carbendazim showed notably elevated mean concentrations ranging from 1.758 to 3.936 mg/kg, with maximum values exceeding 9.103 mg/kg, compared to an MRL of 0.1 mg/kg. Hexaconazole levels ranged from 0.379 to 0.589 mg/kg, also surpassing the MRL of 0.01 mg/kg. In contrast, a limited number of compounds, including pyrimethanil (0.069–0.163 mg/kg) and trifloxystrobin (≤ 0.138 mg/kg), were generally detected at levels below their respective MRLs.

The findings of the present study are consistent with reports from multiple regions documenting frequent pesticide residue contamination in cucumbers. Classification of the detected pesticides according to the WHO toxicity criteria (Fig. 2) revealed that 47.8% of the detected pesticide residues in both cucumber and watermelon samples were moderately hazardous (Class II), 30.4% slightly hazardous (Class III), 17.4% unlikely to present an acute hazard (Class U), and 4.4% highly hazardous (Class Ib). These findings align with those of Kapeleka (2024), who reported that in the Iringa and Arusha regions of Tanzania, 68.9% of fruit and vegetable farmers applied moderately hazardous (Class II) and highly hazardous (Class Ib) pesticides, with the remainder using less hazardous formulations.

Comparable contamination patterns have also been reported in Turkey, where cucumber was identified as one of the commodities most frequently associated with pesticide residue contamination (Çatak and Tiryaki, 2020). Similarly, a nationwide survey conducted across the Southern highlands, Northern and coastal zones of Tanzania found that 74.2% of 613 vegetable samples, including cucumber, contained pesticide residues exceeding authorised MRLs (Kapeleka et al., 2020). Consistent trends have also been observed in Egypt, where Ibrahim and Shalaby (2023) reported that 50% of analysed vegetable samples, including cucumbers, contained residues of acetamiprid and metalaxyl exceeding established MRLs.

In contrast, residue levels reported in some Asian studies were comparatively lower than those observed in the present study. Carbendazim concentrations of 0.012 mg/kg and 0.02 mg/kg in cucumber were reported in China by Xu et al. (2018) and Wang et al. (2024), respectively. However, studies from Iran and Kuwait have documented

Table 2

Levels of pesticide residues detected in cucumber samples and compliance with EU maximum residue limits (N = 25).

Market	Pesticide	Mean mg/kg	Min	Max	MRLs	Compliance
Kisutu	Acephate	6.333	4.535	10.312	0.01	NC
	Thiamethoxam	0.145	0.100	0.196	0.5	C
	Imidacloprid	1.957	1.195	2.851	0.5	NC
	Acetamiprid	1.067	0.026	2.394	0.05	NC
	Dimethoate	0.175	0.063	21.406	0.01	C
	Lufenuron	15.983	0.026	34.653	0.15	NC
	Metribuzin	0.082	0.065	0.090	0.1	C
	Atrazine	0.059	0.029	0.115	0.05	NC
	Carbendazim	3.612	1.066	7.810	0.1	NC
	Metalaxyl	1.906	0.087	6.506	0.5	NC
	Azoxystrobin	0.724	0.080	2.248	1	C
	Pyrimethanil	0.137	0.064	0.214	0.8	C
	Triadimefon	0.046	0.016	0.069	0.01	NC
	Triadimenol	0.070	0.006	0.149	0.01	NC
	Cyproconazole	0.425	0.276	0.566	0.01	NC
	Metolachlor	0.046	0.034	0.067	0.01	NC
	Tebuconazole	0.769	0.336	1.025	0.6	NC
	Hexaconazole	0.595	0.284	1.041	0.01	NC
	Difenoconazole	0.063	0.034	0.078	0.3	C
	Trifloxystrobin	0.138	0.090	0.175	0.3	C
Buguruni	Acephate	4.583	1.281	6.174	0.01	NC
	Thiamethoxam	0.128	0.093	0.165	0.5	C
	Imidacloprid	2.489	1.075	4.331	0.5	NC
	Acetamiprid	0.278	0.016	1.116	0.05	C
	Dimethoate	6.023	0.225	27.367	0.01	NC
	Lufenuron	7.635	5.840	13.635	0.15	NC
	Metribuzin	0.068	0.043	0.094	0.1	C
	Atrazine	0.114	0.009	0.422	0.05	NC
	Carbendazim	2.429	0.817	4.250	0.1	NC
	Metalaxyl	1.114	0.028	3.049	0.5	NC
	Azoxystrobin	2.175	0.043	10.682	1	NC
	Pyrimethanil	0.069	0.032	0.120	0.8	C
	Triadimefon	0.069	0.033	0.119	0.01	NC
	Triadimenol	0.060	0.008	0.126	0.01	NC
	Cyproconazole	0.277	0.046	0.649	0.01	NC
	Metolachlor	0.053	0.030	0.077	0.01	NC
	Tebuconazole	0.504	0.139	0.953	0.6	C
	Hexaconazole	0.379	0.182	0.522	0.01	NC
	Difenoconazole	1.975	0.704	6.646	0.3	NC
	Trifloxystrobin	0.013	0.007	0.016	0.3	C
Ilala	Acephate	6.003	5.474	7.358	0.01	NC
	Thiamethoxam	0.155	0.090	0.196	0.5	C
	Imidacloprid	6.034	1.083	15.713	0.5	NC
	Acetamiprid	0.775	0.022	2.654	0.05	NC
	Dimethoate	1.511	0.014	4.361	0.01	NC
	Lufenuron	7.878	5.530	13.121	0.15	NC
	Metribuzin	0.112	0.035	0.190	0.1	NC
	Atrazine	0.129	0.036	0.435	0.05	NC
	Carbendazim	3.936	0.569	9.103	0.1	NC
	Metalaxyl	1.790	0.055	6.909	0.5	NC
	Azoxystrobin	0.273	0.049	1.000	1	C
	Pyrimethanil	0.163	0.050	0.293	0.8	C
	Triadimefon	0.079	0.047	0.124	0.01	NC
	Triadimenol	0.136	0.062	0.227	0.01	NC
	Cyproconazole	0.496	0.271	0.862	0.01	NC
	Metolachlor	0.047	0.032	0.085	0.01	NC
	Tebuconazole	0.438	0.026	0.819	0.6	C
	Hexaconazole	0.390	0.211	0.695	0.01	NC
	Difenoconazole	0.836	0.633	1.359	0.3	NC
	Trifloxystrobin	0.017	0.008	0.026	0.3	C
Mabibo	Acephate	4.600	1.749	6.579	0.01	NC
	Thiamethoxam	0.089	0.012	0.172	0.5	C
	Imidacloprid	2.436	1.539	4.752	0.5	NC
	Acetamiprid	1.710	0.026	4.352	0.05	NC
	Dimethoate	0.402	0.046	1.068	0.01	NC
	Lufenuron	12.082	4.436	18.863	0.15	NC
	Metribuzin	0.054	0.029	0.073	0.1	C
	Atrazine	0.029	0.023	0.038	0.05	C
	Carbendazim	1.758	0.624	4.498	0.1	NC
	Metalaxyl	1.209	0.092	3.782	0.5	NC
	Azoxystrobin	0.070	0.039	0.101	1	C
	Pyrimethanil	0.099	0.025	0.210	0.8	C
	Triadimefon	0.082	0.040	0.128	0.01	NC

(continued on next page)

Table 2 (continued)

Market	Pesticide	Mean mg/kg	Min	Max	MRLs	Compliance
Veterinary	Triadimenol	0.097	0.019	0.186	0.01	NC
	Cyproconazole	0.314	0.171	0.646	0.01	NC
	Metolachlor	0.038	0.028	0.044	0.01	NC
	Tebuconazole	0.261	0.154	0.387	0.6	C
	Hexaconazole	0.589	0.262	1.024	0.01	NC
	Difenoconazole	0.789	0.708	0.863	0.3	NC
	Trifloxystrobin	0.015	0.009	0.024	0.3	C
	Acephate	2.917	1.514	3.809	0.01	NC
	Thiamethoxam	0.155	0.028	0.230	0.5	C
	Imidacloprid	2.209	1.219	4.311	0.5	NC
	Acetamiprid	0.247	0.018	1.140	0.05	NC
	Dimethoate	0.625	0.449	0.926	0.01	NC
	Lufenuron	9.160	6.275	14.384	0.15	NC
	Metribuzin	0.119	0.043	0.313	0.1	NC
	Atrazine	0.079	0.029	0.185	0.05	NC
	Carbendazim	2.429	0.273	6.168	0.1	NC
	Metalaxyl	0.901	0.086	4.098	0.5	NC
	Azoxystrobin	0.056	0.039	0.090	1	C
	Pyrimethanil	0.115	0.060	0.202	0.8	C
	Triadimefon	0.074	0.021	0.107	0.01	NC
	Triadimenol	0.062	0.020	0.130	0.01	NC
	Cyproconazole	0.177	0.117	0.317	0.01	NC
	Metolachlor	0.036	0.023	0.051	0.01	NC
	Tebuconazole	0.487	0.376	0.556	0.6	C
	Hexaconazole	0.403	0.199	1.183	0.01	NC
	Difenoconazole	1.251	1.108	1.542	0.3	NC
	Trifloxystrobin	0.017	0.009	0.029	0.3	C

C - comply, NC - not comply, min - minimum concentration, max - maximum concentration, MRLs - maximum residue limits (Source: European Union under Regulation (EC) No 396/2005).

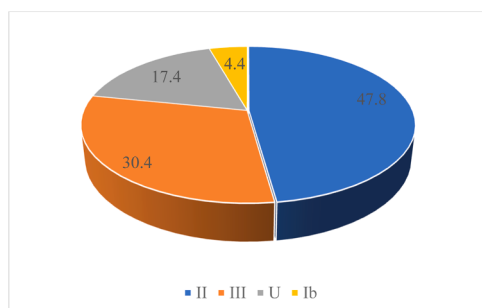


Fig. 2. WHO pesticide toxicity classification and corresponding percentages of the detected pesticide compounds.

the presence of both insecticides and fungicides in cucumbers, including imidacloprid (0.065–1.2 mg/kg) and tebuconazole (0.026 mg/kg), underscoring the widespread use of these residues in intensive vegetable farming (Jallow et al., 2017; Mahdavi et al., 2022).

3.2. Pesticide residue concentrations in watermelon

The concentration levels of pesticide residues detected in watermelon samples, including the minimum, maximum, and mean values, along with their corresponding MRLs and compliance status, are presented in Table 3. The findings indicate extensive contamination, with most detected pesticides exceeding established MRLs, indicating significant non-compliance with food safety regulations. Since the produce is widely sourced across the Pwani Region, the observed residue patterns likely stem from pre-harvest pesticide practices at the farm level rather than market-specific factors.

Neonicotinoid insecticides, namely thiamethoxam, imidacloprid, and acetamiprid, were frequently detected at concentrations exceeding their respective MRLs, indicating widespread, poorly regulated use of this insecticide class in watermelon cultivation. Imidacloprid exhibited particularly elevated levels, with mean concentrations ranging from

1.957 to 6.034 mg/kg and a maximum of 15.713 mg/kg, far above the permissible limits of 0.15 mg/kg. Thiamethoxam was also detected at relatively consistent concentrations (0.089–0.155 mg/kg) across samples; however, these levels remained above the established MRLs of 0.01 mg/kg. Acetamiprid was detected at concentrations exceeding MRLs in all samples, with mean levels ranging from 0.247 to 1.710 mg/kg. Collectively, these findings indicate extensive neonicotinoid use in watermelon production, with minimal adherence to recommended application rates and pre-harvest intervals. Furthermore, the organophosphate insecticide dimethoate was detected at excessively high levels, with mean concentrations up to 6.023 mg/kg and a maximum of 27.367 mg/kg, well above established MRLs, indicating inappropriate pesticide application practices and raising significant concerns about chronic dietary exposure.

In addition, among fungicides, carbendazim, metalaxyl, cyproconazole, hexaconazole, triadimenol, and difenoconazole were consistently detected at concentrations exceeding their respective MRLs across samples. Carbendazim exhibited markedly elevated residue levels, with mean concentrations ranging from 1.758 to 3.936 mg/kg and maximum values reaching 9.103 mg/kg, substantially above its MRL of 0.1 mg/kg. Metalaxyl was also detected at concentrations exceeding regulatory limits, with mean values ranging from 0.901 to 1.906 mg/kg and maximum levels reaching 6.909 mg/kg, significantly above the MRL of 0.15 mg/kg. Similarly, cyproconazole was consistently detected at levels above its permissible limit, with mean concentrations ranging from 0.177 to 0.496 mg/kg, compared to an MRL of 0.05 mg/kg. Cyproconazole, hexaconazole, triadimenol, and difenoconazole also demonstrated persistent MRL exceedances across samples, with difenoconazole recording peak values of 6.646 mg/kg against a permissible limit of 0.2 mg/kg. These findings collectively indicate widespread non-compliance with fungicide use at the production level. In contrast, a limited number of pesticides were detected within accepted limits. Metribuzin showed acceptable mean concentrations (0.068–0.082 mg/kg) in some samples, remaining within the MRL of 0.1 mg/kg, although exceedances were observed in others. Similarly, dimethomorph was detected at low concentrations (0.031–0.040 mg/kg), well below its

Table 3

Concentration of pesticide residues in watermelon samples and compliance with EU maximum residue limits (N = 25).

Market	Pesticide compound	Mean	Min	Max	MRLs	Compliance
		mg/kg				
Kisutu	Thiamethoxam	0.145	0.100	0.196	0.01	NC
	Imidacloprid	1.957	1.195	2.851	0.15	NC
	Acetamiprid	1.067	0.026	2.394	0.08	NC
	Dimethoate	4.808	0.063	21.406	0.01	NC
	Metribuzin	0.082	0.065	0.090	0.1	C
	Atrazine	0.059	0.029	0.115	0.05	NC
	Carbendazim	3.612	1.066	7.810	0.1	NC
	Metalaxyl	1.906	0.087	6.506	0.15	NC
	Dimethomorph	0.031	0.008	0.058	0.5	C
	Triadimefon	0.046	0.016	0.069	0.01	NC
	Triadimenol	0.070	0.006	0.149	0.01	NC
	Cyproconazole	0.425	0.276	0.566	0.05	NC
	Hexaconazole	0.595	0.284	1.041	0.01	NC
	Difenoconazole	1.000	0.727	1.358	0.2	NC
	Spirotetramat	0.405	0.150	0.681	0.2	NC
	Quizalofop-ethyl	0.020	0.006	0.027	0.01	NC
Buguruni	Thiamethoxam	0.128	0.093	0.165	0.01	NC
	Imidacloprid	2.489	1.075	4.331	0.15	NC
	Acetamiprid	0.278	0.016	1.116	0.08	NC
	Dimethoate	6.023	0.225	27.367	0.01	NC
	Metribuzin	0.068	0.043	0.094	0.1	C
	Atrazine	0.114	0.009	0.422	0.05	NC
	Carbendazim	2.429	0.817	4.250	0.1	NC
	Metalaxyl	1.114	0.028	3.049	0.15	NC
	Dimethomorph	0.040	0.029	0.045	0.5	C
	Triadimefon	0.069	0.033	0.119	0.01	NC
	Triadimenol	0.060	0.008	0.126	0.01	NC
	Cyproconazole	0.277	0.046	0.649	0.05	NC
	Hexaconazole	0.380	0.182	0.522	0.01	NC
	Difenoconazole	1.975	0.704	6.646	0.2	NC
	Spirotetramat	0.338	0.010	0.614	0.2	NC
	Quizalofop-ethyl	0.010	0.005	0.018	0.01	C
Ilala	Thiamethoxam	0.155	0.090	0.196	0.01	NC
	Imidacloprid	6.034	1.083	15.713	0.15	NC
	Acetamiprid	0.775	0.022	2.654	0.08	NC
	Dimethoate	1.511	0.014	4.361	0.01	NC
	Metribuzin	0.112	0.035	0.190	0.1	NC
	Atrazine	0.129	0.036	0.435	0.05	NC
	Carbendazim	3.936	0.569	9.103	0.1	NC
	Metalaxyl	1.790	0.055	6.909	0.15	NC
	Dimethomorph	0.098	0.054	0.209	0.5	C
	Triadimefon	0.079	0.047	0.124	0.01	NC
	Triadimenol	0.136	0.062	0.227	0.01	NC
	Cyproconazole	0.496	0.271	0.862	0.05	NC
	Hexaconazole	0.390	0.211	0.695	0.01	NC
	Difenoconazole	0.836	0.633	1.359	0.2	NC
	Spirotetramat	0.685	0.283	1.046	0.2	NC
	Quizalofop-ethyl	0.016	0.007	0.020	0.01	NC
Mabibo	Thiamethoxam	0.089	0.012	0.172	0.01	NC
	Imidacloprid	2.436	1.539	4.752	0.15	NC
	Acetamiprid	1.710	0.026	4.352	0.08	NC
	Dimethoate	0.402	0.046	1.068	0.01	NC
	Metribuzin	0.054	0.029	0.073	0.1	C
	Atrazine	0.029	0.023	0.038	0.05	C
	Carbendazim	1.758	0.624	4.498	0.1	NC
	Metalaxyl	1.209	0.092	3.782	0.15	NC
	Dimethomorph	0.044	0.033	0.057	0.5	C
	Triadimefon	0.082	0.040	0.128	0.01	NC
	Triadimenol	0.097	0.019	0.186	0.01	C
	Cyproconazole	0.314	0.171	0.646	0.05	NC
	Hexaconazole	0.589	0.262	1.024	0.01	NC
	Difenoconazole	0.790	0.708	0.863	0.2	NC
	Spirotetramat	0.671	0.278	1.162	0.2	NC
	Quizalofop-ethyl	0.018	0.009	0.037	0.01	NC
Veterinary	Thiamethoxam	0.155	0.028	0.230	0.01	NC
	Imidacloprid	2.210	1.219	4.311	0.15	NC
	Acetamiprid	0.247	0.018	1.140	0.08	NC
	Dimethoate	0.625	0.449	0.926	0.01	NC
	Metribuzin	0.119	0.043	0.313	0.1	NC
	Atrazine	0.079	0.029	0.185	0.05	C
	Carbendazim	2.429	0.273	6.168	0.1	NC
	Metalaxyl	0.901	0.086	4.098	0.15	NC

(continued on next page)

Table 3 (continued)

Market	Pesticide compound	Mean	Min	Max	MRLs	Compliance
	Dimethomorph	0.057	0.042	0.068	0.5	C
	Triadimefon	0.074	0.021	0.107	0.01	NC
	Triadimenol	0.062	0.020	0.130	0.01	NC
	Cyproconazole	0.177	0.117	0.317	0.05	NC
	Hexaconazole	0.403	0.199	1.183	0.01	NC
	Difenoconazole	0.734	0.709	0.779	0.2	NC
	Spirotetramat	0.585	0.063	1.265	0.2	NC
	Quizalofop-ethyl	0.015	0.007	0.038	0.01	NC

C - compliance, NC - non-compliance, min - minimum concentration, max - maximum concentration, MRLs -maximum residue limits (Source: European Union under Regulation (EC) No 396/2005).

MRL of 0.5 mg/kg. Atrazine was within permissible limits in most samples.

Watermelon samples in the present study showed pesticide residues exceeding established MRLs, raising serious food safety concerns. This stands in contrast to findings from Egypt, where Ibrahim and Shalaby (2023) reported that all analysed watermelon samples (N = 114, 100%) were contaminated with acetamiprid, yet residue levels remained within regulatory limits. The disparity between these findings likely reflects differences in pesticide application rates, agronomic practices, and the stringency of regulatory oversight between the two regions. The residue profile observed in the present study, characterised by the predominance of neonicotinoid insecticides, particularly imidacloprid and acetamiprid, is consistent with reports from other regions. Studies conducted in China and Jordan have documented frequent detection of neonicotinoids in cucurbits, including measurable imidacloprid residues of up to 0.12 mg/kg in watermelon (Zhou et al., 2023; Al-Hawadi et al., 2023). Furthermore, acephate residues of up to 0.45 mg/kg in watermelon have been reported in the United Arab Emirates (Osaili et al., 2022), further supporting the extensive use of broad-spectrum pesticides in cucurbit production across multiple geographic contexts.

With respect to organophosphate residues, the levels of dimethoate detected in the present study were notably higher than those reported in European studies, where organophosphate use has diminished due to stringent regulatory measures and the adoption of novel chemistries (Buonsenso, 2025). In contrast, monitoring studies from several African and Asian countries continue to report detectable dimethoate residues in watermelon, indicating ongoing use of outdated broad-spectrum insecticides in these regions (Gelaye and Negash, 2024; Shoeibi et al., 2017). This difference highlights regional variations in pesticide use patterns, limited extension services, and the effectiveness of regulatory enforcement where such compounds remain in active use.

Overall, both cucumber and watermelon samples had high pesticide residue levels, exceeding the established MRLs and indicating non-compliance. Imidacloprid (1.96–6.03 mg/kg; highest: 15.71 mg/kg) and acetamiprid (0.25–1.71 mg/kg) were frequently present at high concentrations in both commodities, as was thiamethoxam (0.09–0.16 mg/kg). Dimethoate, an organophosphate insecticide, exceeded mean concentrations of 6.02 mg/kg and maximum values of 27 mg/kg. Fungicides such as carbendazim (1.76–3.94 mg/kg; maximum: 9 mg/kg), hexaconazole (0.38–0.60 mg/kg), cyproconazole (0.1–0.50 mg/kg), triadimenol (0.06–0.14 mg/kg), difenoconazole (0.73–1.98 mg/kg; maximum: 6.65 mg/kg), and metalaxyl frequently exceeded their MRLs. Watermelon samples exhibited higher residue levels and more exceedances than cucumber samples, although both commodities displayed similar contamination patterns. Variations in residue concentrations suggest improper pesticide application, including excessive use and non-compliance with recommended dosing and pre-harvest intervals (Kilemle et al., 2026). Other pesticides, including azoxystrobin and trifloxystrobin, were detected at levels below permissible limits, demonstrating that compliance is possible with proper management. Given the pre-harvest practices observed in

the Pwani Region, contamination in both commodities is likely attributable to production-level factors rather than market-specific features.

The high rates of MRL exceedances observed in this study (70–85%) are among the highest reported globally for cucurbit vegetables. Comparable studies from other African countries have reported lower exceedance rates: 48% in Ghana (Bempah et al., 2011), 52% in Ethiopia (Gelaye and Negash, 2024), and 62% in Egypt (Ibrahim and Shalaby, 2023). Studies from Asia and Europe report substantially lower exceedance rates (typically 5–25%), reflecting more stringent regulatory enforcement and better farmer compliance with pre-harvest intervals (Çatak and Tiryaki, 2020; Mahdavi et al., 2022; Zhou et al., 2023). Al-Hababeh et al. (2025) reported that in Jordan, 77.7% of fruit and vegetable samples were contaminated with pesticide residues that exceeded the set MRLs.

3.3. Health risk assessment in cucumber

Table 4 presents the mean residue levels, EDI, ADI, HI, and risk classifications for both adults and children derived from cucumber consumption. A notable limitation in the risk characterisation is that HI calculations were infeasible for acephate and dimethoate due to the lack of defined ADI values in the EU toxicological database, despite their comparatively elevated mean concentrations of 4.88 mg/kg and 1.75 mg/kg, respectively. This gap in toxicological reference data substantially undermines the comprehensiveness of the health risk assessment and underscores a critical deficiency in regulatory databases for several widely used pesticide residues. Nevertheless, the findings reveal significant variation in dietary exposure and risk across pesticide classes, with children consistently facing greater risk than adults due to their lower body weight and higher consumption per unit body mass (Fig. 3).

For adult consumers, the majority of pesticides with defined ADI values yielded HI values below the critical threshold of 100%, indicating no substantial chronic dietary risk under the estimated consumption scenario. Nonetheless, notably elevated adult HI values were recorded for lufenuron (189.9%), acetamiprid (54.8%), carbendazim (38.2%), difenoconazole (26.5%), and hexaconazole (25.5%), indicating significant exposure levels that warrant regulatory attention. Lufenuron, detected at a mean concentration of 10.55 mg/kg relative to its MRL of 0.15 mg/kg, resulted in an adult HI substantially exceeding 100%, indicating an unacceptable chronic exposure risk even for adult consumers.

Using the binary HI threshold ($\leq 100\%$ = acceptable risk; $> 100\%$ = unacceptable risk), three pesticides exceeded the acceptable threshold for children: lufenuron (682.1%), acetamiprid (196.9%), and carbendazim (137.4%). These values indicate a potential chronic health concern for children consuming cucumbers at current consumption rates. Two additional pesticides, hexaconazole (91.6%) and difenoconazole (95.4%), produced HI values below the 100% threshold but close to it, suggesting that exposure levels are near the maximum tolerable intake. For adult consumers, most pesticides with defined ADI values had HI values below 100%, indicating acceptable chronic risk under the estimated consumption scenario. This heightened vulnerability in

Table 4

Residue concentrations, estimated daily intake (EDI), acceptable daily intake (ADI), hazard index (HI), risk classification (RC), and cumulative HI for pesticide residues detected in cucumber samples (N = 25).

Pesticide compound	Mean (mg/kg)	EDI-adults (mg/kg bw day ⁻¹)	EDI-children (mg/kg bw day ⁻¹)	ADI	HI-adults (%)	RC-adult	HI-children (%)	RC-children
Acephate	4.881	0.013	0.047	NA	NA	NA	NA	NA
Thiamethoxam	0.135	0.0004	0.0013	0.026	1.5	Acceptable	5.0	Acceptable
Imidacloprid	3.825	0.0103	0.037	0.060	17.2	Acceptable	61.7	Acceptable
Acetamiprid	1.015	0.003	0.0098	0.005	60.0	Acceptable	196.0	Unacceptable
Dimethoate	1.747	0.005	0.017	NA	NA	NA	NA	NA
Lufenuron	10.548	0.029	0.1023	0.015	193.3	Unacceptable	682.0	Unacceptable
Metribuzin	0.087	0.0002	0.001	0.0013	15.4	Acceptable	76.9	Acceptable
Atrazine	0.082	0.0002	0.001	0.020	1.0	Acceptable	5.0	Acceptable
Carbendazim	2.833	0.008	0.028	0.020	40.0	Acceptable	140.0	Unacceptable
Metaxyl	1.384	0.004	0.0134	0.080	5.0	Acceptable	16.8	Acceptable
Azoxystrobin	0.660	0.002	0.006	0.200	1.0	Acceptable	3.0	Acceptable
Pyrimethanil	0.117	0.0003	0.001	0.170	0.2	Acceptable	0.6	Acceptable
Triadimefon	0.070	0.0002	0.001	0.030	0.7	Acceptable	3.3	Acceptable
Triadimenol	0.085	0.0002	0.001	0.050	0.4	Acceptable	2.0	Acceptable
Cyproconazole	0.338	0.001	0.003	0.020	5.0	Acceptable	15.0	Acceptable
Metolachlor	0.044	0.0001	0.0004	0.10	0.1	Acceptable	0.4	Acceptable
Tebuconazole	0.492	0.0013	0.005	0.030	4.3	Acceptable	16.7	Acceptable
Hexaconazole	0.472	0.0013	0.005	0.005	26.0	Acceptable	100.0	Acceptable
Difenoconazole	0.983	0.003	0.0095	0.010	30.0	Acceptable	95.0	Acceptable
Trifloxystrobin	0.040	0.0001	0.0004	0.100	0.1	Acceptable	0.4	Acceptable
HI - cumulative					401.2		1419.8	

Where NA = Not available (ADI not established in the EU Pesticides Database), risk classification could not be determined for these compounds.

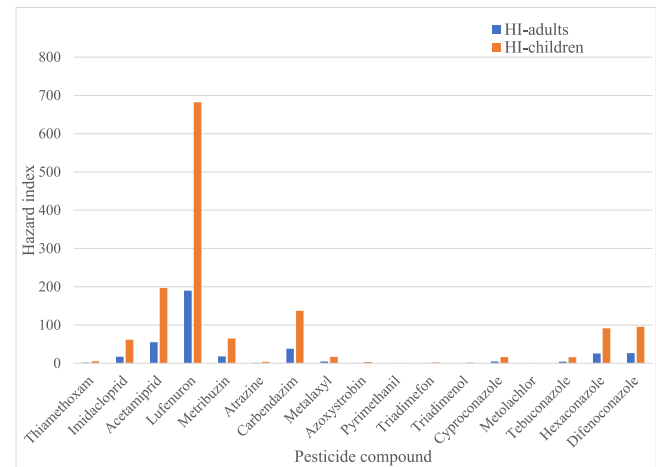


Fig. 3. Hazard Index comparison between adults and children for pesticide residues detected in cucumber samples.

children is well documented and is primarily attributable to their higher food intake relative to body weight, combined with their immature physiological and metabolic detoxification systems, which substantially reduce their capacity to metabolise and eliminate pesticide residues compared with adults (Cavalier et al., 2023).

The findings of this study are broadly consistent with evidence from previous research associating the consumption of pesticide-contaminated cucumbers and watermelons with potential health risks, including cancer and other adverse health outcomes (Bansal, 2025; Kazar Soydan et al., 2021; Khoshnam et al., 2022; Odewale et al., 2022; Si et al., 2021; Tudi et al., 2022; Zhang et al., 2021). Other pesticides, including thiamethoxam, imidacloprid, metribuzin, atrazine, metalaxyl, azoxystrobin, pyrimethanil, triadimefon, triadimenol, cyproconazole, metolachlor, tebuconazole, and trifloxystrobin, demonstrated HI values well below 100% for both adults and children, indicating minimal chronic risk from individual exposure at current consumption levels. Collectively, the findings indicate that cucumber consumption does not pose a significant chronic dietary risk to adults for most pesticides; nevertheless, children may experience potentially harmful exposure to

certain insecticides and fungicides, including lufenuron, acetamiprid, and carbendazim. The persistent exceedance of MRLs and unacceptable HI values underscore the urgent need for improved pesticide management, rigorous enforcement of pre-harvest intervals, and consistent residue monitoring, especially to protect vulnerable groups such as children.

3.4. Health risk assessment in watermelon

The health risk assessment for watermelon consumption, based on EDI, ADI, and HI indicators, is presented in Table 5. The results indicate a clear population-dependent risk pattern, with children exhibiting considerably greater exposure and risk levels than adults, attributable to their lower body weight and proportionately higher food intake per unit of body mass.

For adult consumers, the majority of pesticides with documented ADI values had HI values well below the critical threshold of 100%, indicating no substantial chronic dietary risk from watermelon intake under the estimated exposure scenario. The highest adult HI values were recorded for acetamiprid (44%), carbendazim (36.8%), difenoconazole (28.8%), and hexaconazole (25.5%), all of which remained within acceptable safety thresholds (Fig. 4). Risk characterisation for dimethoate could not be performed owing to the absence of an EU pesticide database ADI value, introducing uncertainty about its long-term health effects despite its comparatively elevated mean concentration in the samples.

Children were identified as a particularly susceptible population, with several pesticide residues exceeding the HI safety threshold of 100% (Fig. 4). Applying the same binary HI threshold, three pesticides exceeded 100% for children: acetamiprid (158.2%), carbendazim (132.1%), and difenoconazole (103.5%), indicating potential chronic health hazards associated with regular watermelon consumption among this age group. Hexaconazole (91.5%) remained below the 100% threshold but was close to it, warranting close monitoring. For adult consumers, the majority of pesticides with documented ADI values had HI values well below 100%.

The health risk findings from the present study are not entirely consistent with those reported in other studies. A study by Okrikata et al. (2022) reported a negligible health risk associated with watermelon consumption in Nigeria. However, their study also concluded that

Table 5

Residue concentrations, estimated daily intake (EDI), acceptable daily intake (ADI), hazard index (HI), risk classification (RC), and cumulative HI for pesticide residues detected in watermelon samples (N = 25).

Pesticide compound	Mean (mg/kg)	EDI-adult	EDI-children	ADI	HI-adults (%)	RC-adult	HI-children (%)	RC-children
		(mg/kg bw day ⁻¹)						
Thiamethoxam	0.135	0.000	0.001	0.026	0	Acceptable	3.8	Acceptable
Imidacloprid	3.025	0.008	0.029	0.060	13.3	Acceptable	48.3	Acceptable
Acetamiprid	0.815	0.002	0.008	0.005	40.0	Acceptable	160.0	Unacceptable
Dimethoate	2.883	0.008	0.028	NA	NA	NA	NA	NA
Metribuzin	0.090	0.000	0.001	0.0013	0	Acceptable	76.9	Acceptable
Atrazine	0.082	0.000	0.001	0.020	0	Acceptable	5.0	Acceptable
Carbendazim	2.724	0.007	0.026	0.020	35.0	Acceptable	130.0	Unacceptable
Metaxyl	1.384	0.004	0.013	0.080	5.0	Acceptable	16.3	Acceptable
Dimethomorph	0.055	0.000	0.001	0.050	0	Acceptable	2.0	Acceptable
Triadimefon	0.071	0.000	0.001	0.030	0	Acceptable	3.3	Acceptable
Triadimenol	0.082	0.000	0.001	0.050	0	Acceptable	2.0	Acceptable
Cyproconazole	0.334	0.001	0.003	0.020	5.0	Acceptable	15.0	Acceptable
Hexaconazole	0.471	0.001	0.005	0.005	20.0	Acceptable	100.0	Acceptable
Difenoconazole	1.067	0.003	0.010	0.010	30.0	Acceptable	100.0	Acceptable
Spirotetramat	0.542	0.001	0.005	0.050	2.0	Acceptable	10.0	Acceptable
Quinalofop-ethyl	0.015	0.000	0.000	0.009	0	Acceptable	0.0	Acceptable
HI - cumulative					150.5		672.6	

Where: NA = Not available (ADI not established in the EU Pesticides Database); risk classification could not be determined for these compounds.

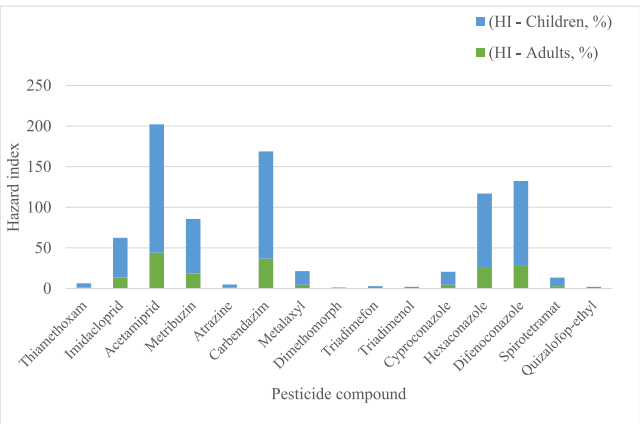


Fig. 4. Hazard Index comparison between adults and children for pesticide residues detected in watermelon samples.

children were more susceptible to health risks than adults, a finding consistent with the present study. The disparity in overall risk levels between the two studies likely reflects differences in pesticide application intensities, farming practices, and regulatory environments between the respective study regions. Furthermore, a study conducted in China reported minimal risk associated with both long-term chronic and short-term acute dietary exposure to difenoconazole pesticide, with exposure levels remaining within safety limits (Li et al., 2025; Ling et al., 2021), further highlighting the regional dependence of dietary risk profiles and the importance of localised monitoring data.

3.5. Cumulative health risk

The cumulative Hazard Index, calculated as the sum of individual HI values for all detected pesticides in each sample, provides a more realistic estimate of combined dietary exposure than single-compound assessments. In the present study, cumulative HI values exceeded the acceptable threshold of 100% in 100% of contaminated samples (N = 50), indicating unacceptable cumulative dietary exposure for consumers of cucumber and watermelon in Dar es Salaam city. The highest cumulative HI recorded for cucumber samples was 1419.8% for children and 401.2% for adults; for watermelon samples, it was 672.7% for children and 150.3% for adults. These values indicate that children face a cumulative exposure burden approximately 14 times higher than

the acceptable threshold from cucumber consumption alone.

These findings align with recent studies reporting elevated cumulative risks from pesticide mixtures in vegetables. A 2025 study from Ghana reported combined organophosphate and neonicotinoid hazard indices significantly exceeding the safety threshold (HI > 1), with children facing greater health risks than adults, particularly for lettuce and cabbage samples from high-temperature urban farming zones (Kumah et al., 2025). Similarly, a 2025 study in Serbia found that whilst individual hazard quotients remained below concern levels, cumulative acute risks reached 63.1% of the Acute Reference Dose (ARfD) for children — substantially higher than the 51.1% ARfD observed for adults (Lucić and Onjia, 2025). The Serbian study also confirmed, through sensitivity analysis, that body weight and vegetable consumption rates are the most influential factors in chronic risk variability, consistent with the present study's finding that children's lower body weight is a primary driver of elevated HI values. In Poland, a study by Lozowicka et al. (2016) also found that cumulative HI values in vegetables exceeded acceptable thresholds through dietary consumption, although the levels recorded were lower than those reported in the present study.

Furthermore, for cucurbit crops specifically, a 2024 probabilistic risk assessment from Iran reported that hazard index values for carbamates, pyrethroids, and organophosphorus compounds in cucumber, melon, and watermelon remained below safety thresholds for Iranian consumers (Mahdavi et al., 2024). The contrast between these findings and the elevated cumulative risks observed in the present study likely reflects differences in pesticide application practices, regulatory enforcement, and pre-harvest interval compliance between Iran and Tanzania. While the Iranian study found mean levels of carbaryl, methomyl, diazinon, malathion, and methamidophos exceeding MRLs in farmland crops, their cumulative HI values nevertheless remained below concern levels (Mahdavi et al., 2024). This suggests that MRL exceedance alone does not necessarily translate to an unacceptable health risk. This finding underscores the importance of conducting ADI-based cumulative risk assessments rather than relying solely on MRL compliance rates.

A 2025 study from China employing multi-model risk assessment (including both HI and Relative Potency Factor models) reported that whilst chronic cumulative exposure risks from fruits remained acceptable, the HI model significantly underestimated acute neurotoxicity and hepatotoxicity risks (by 4–7 times) compared to the more sophisticated RPF model (Si et al., 2025). This finding has important implications for the present study: the cumulative values reported here (reaching 1419.8% for children) may represent conservative estimates, as actual

health risks could be higher if synergistic interactions among co-occurring pesticides are taken into account. The study by Si et al. (2025) also identified difenoconazole as a high-risk compound, consistent with the present study's finding that difenoconazole HI exceeded 100% in children from watermelon samples (103.5%). This consistent pattern across diverse geographical contexts supports the conclusion that children's physiological characteristics — higher food intake per kg of body weight, immature detoxification systems, and developing organ systems — make them a universally vulnerable population that requires specific consideration in food safety regulation. Furthermore, the substantially higher cumulative risks observed in the present study likely reflect more intensive pesticide application practices in Tanzanian cucurbit production and inadequate compliance with pre-harvest intervals, as documented in a companion knowledge, attitudes, and practices (KAP) study (Kilemle et al., 2026).

3.6. Comparative health risk assessment of pesticide residues in cucumber and watermelon

A comparative assessment of dietary health risk associated with cucumber and watermelon consumption indicated a persistent pattern of increased susceptibility in children across both commodities, whilst showing significant disparities in the extent of risk and in the pesticide-specific factors influencing risk between the two commodity types (Figs. 3 and 4). The chronic risk profile for cucumber was primarily influenced by lufenuron (HI - children = 682.1%), acetamiprid (196.9%), and carbendazim (137.4%), indicating the combined effect of high residue concentrations and relatively low ADI thresholds for these compounds. Fungicides such as hexaconazole (91.6%) and difenoconazole (95.4%) were close to the risk threshold, representing cumulative exposure concerns despite individual HI values remaining below 100% (Table 4).

In watermelon, children were similarly exposed to hazardous levels of acetamiprid (158.2%), carbendazim (132.1%), and difenoconazole (103.5%), whilst hexaconazole (91.5%) was considered a compound of significant concern (Table 5). However, the overall risk intensity in watermelon was comparatively lower than in cucumber, with fewer compounds exceeding the HI threshold and lower maximum HI values. For adult consumers, both commodities had HI values below 100% for most pesticides with defined ADIs, indicating acceptable chronic risk at current consumption levels.

These data collectively suggest that cucumber presents a greater chronic dietary risk than watermelon, especially for children, highlighting the need for commodity-specific risk management and enhanced regulatory enforcement. Comparative evidence from previous studies consistently shows that cucumbers pose a greater risk for dietary pesticide exposure than watermelons (Karimi et al., 2025). This differential is largely linked to differences in consumption habits: cucumbers are typically consumed raw and unpeeled, resulting in the direct ingestion of both surface-bound and systemically distributed pesticide residues. This observation is consistent with comparative evidence from previous studies conducted across Asia, Africa, and the Middle East, which have similarly reported that cucumbers frequently pose greater health risks compared to watermelon (Alsaikhan et al., 2021; Bempah et al., 2011; Ibrahim and Shalaby, 2023; Kazar Soydan et al., 2021; Mahdavi et al., 2022).

3.7. Farm-level practices as drivers of residue variability

The variation in pesticide residue levels observed across samples reflects differences in pesticide application practices during the production stage, rather than market-specific factors. As illustrated in Table 2, persistently elevated concentrations of multiple pesticide residues across samples indicate extensive misuse, characterised by excessive application rates and inadequate compliance with pre-harvest intervals. This trend is further supported by the dietary risk assessment

results (Tables 4 and 5), which indicate that elevated HI and cumulative HI, particularly in children, pose substantial exposure risks. Given that the produce is predominantly sourced from the Pwani Region, the observed variability is likely attributable to differences in agricultural techniques, pesticide application intensity, and adherence to safety regulations (Kilemle et al., 2026).

The elevated levels suggest that produce sold in these markets is sourced from intensive agricultural systems characterised by frequent pesticide use, as evidenced by widespread MRL exceedances (Tables 2 and 3) and high HI values (Tables 4 and 5), indicating inadequate compliance with recommended pesticide use practices. Conversely, certain samples exhibited relatively low residual levels of specific herbicides and fungicides, such as atrazine and metribuzin, suggesting occasional, inconsistent compliance with recommended application rates and pre-harvest intervals.

The observed variation in pesticide residue levels across samples can therefore be more accurately attributed to differences in production practices and supply chains that source produce from both peri-urban and rural farming (Kilemle et al., 2026; Malekela and Nyomora, 2018). These production zones are characterised by varying agricultural practices, pesticide use patterns, and post-harvest handling methods, which collectively influence the observed residue profiles. Similar variability has been documented in other studies, in which differences in residue levels have been linked to heterogeneous agricultural practices, diverse production clusters, and inconsistent extension services (Al-Hawadi et al., 2023; El-Sheikh et al., 2022; Zhou et al., 2023).

3.8. Multiple pesticide residues

The frequent presence of multiple pesticide residues in individual samples is a significant finding of this study, particularly in cucumber, where different insecticides, fungicides, and herbicides were consistently co-detected (Table 2). Whilst individual HI values were calculated separately for each compound (Tables 4 and 5), consumers routinely ingest combinations of pesticide residues in their daily diet. Such combined exposures may produce synergistic effects, particularly among compounds sharing similar mechanisms of action (Hernández et al., 2017; Rizzati et al., 2016), though the present study did not experimentally assess mixture toxicity. The elevated cumulative PTI values recorded in both cucumber and watermelon samples quantify the cumulative exposure burden and underscore the need to incorporate combination toxicity into dietary risk assessments, rather than relying exclusively on single-compound evaluations.

Multi-residue pesticide contamination in cucurbits has been widely reported in other studies (Mahdavi et al., 2022; Malhat et al., 2025). This is likely a consequence of applying different types of pesticides to protect crops against various insect pests and diseases, especially in fruit and vegetable production. Similar trends are observed worldwide, particularly in intensive horticultural systems. A greenhouse cucumber survey in Iran documented multi-residue contamination attributable to high spraying frequencies in protected-cultivation environments (Mahdavi et al., 2022). A nationwide survey in China similarly found that watermelons had the highest proportion of multi-residue contamination, with residues detected in more than half of the analysed samples (Si et al., 2021; Zhang et al., 2021). Furthermore, Jallow et al. (2017) reported that 58% of smallholder vegetable farmers in Kuwait exceeded recommended pesticide application rates, further demonstrating how over-application contributes to residue accumulation and multi-residue profiles at harvest.

3.9. Public health and regulatory implications

The prevalent detection of pesticide residues above established MRLs, combined with HI exceedances for children across multiple compounds in both commodities (Tables 4 and 5), underscores substantial gaps in pesticide regulation and food safety oversight in the

studied area. The consistent detection of high-risk pesticide residues, including lufenuron, acetamiprid, carbendazim, and difenoconazole, at levels that substantially exceed regulatory thresholds is particularly concerning from a public health perspective. Although acute toxicity may not be immediately apparent at the detected exposure levels, the chronic nature of dietary pesticide exposure from regular consumption of contaminated produce poses a potential long-term health concern, particularly for children, who showed HI values exceeding safety thresholds for multiple pesticides. However, HI values for adult consumers remained below 100% for most pesticides with defined ADIs, suggesting that chronic risk to the general adult population may be acceptable under current consumption patterns.

The finding that adult HI values consistently remained below 100% for the majority of compounds with established ADIs, whilst children exhibited HI exceedances for multiple pesticides across various commodities, underscores the established notion that regulatory thresholds predicated on adult physiology are inadequate for safeguarding the paediatric population. Children's increased susceptibility is fundamentally due to their lower body weight relative to food intake, their underdeveloped hepatic detoxification capacity, and their developing neurological and endocrine systems, which collectively enhance the toxic effects of equivalent residue concentrations compared with adults (Cavalier et al., 2023; Lozowicka et al., 2016). These findings suggest that consideration should be given to integrating age-specific and vulnerability-adjusted risk criteria into national food safety frameworks. However, further research and stakeholder consultation would be required to determine the feasibility of and appropriate implementation of such criteria.

The repeated identification of residues above MRLs across all sampled areas, combined with the uniformly elevated cumulative-HI values recorded in both commodities, indicates gaps in farm-level pesticide management. These gaps encompass incorrect dosing and application frequencies, widespread non-compliance with pre-harvest intervals, limited farmer awareness of safe pesticide handling practices, and inadequate enforcement of existing regulatory requirements, observations consistent with the broader pattern of pesticide misuse documented in Sub-Saharan African horticultural systems (Bhawan, 2022; Kapeleka et al., 2020; Kilemire et al., 2026).

Addressing these challenges demands a coordinated and multi-tiered regulatory response. In the immediate term, TPHPA and TBS should prioritise the expansion and rigorous enforcement of routine pesticide residue monitoring programmes, with particular emphasis on the consumption of raw commodities and vulnerable population groups, including children. In the medium term, farmer extension services should be substantially strengthened to promote the adoption of safe pesticide application practices, adherence to pre-harvest intervals, and the use of integrated pest management strategies as sustainable alternatives to broad-spectrum chemical control. Evidence from studies conducted in regions with more robust regulatory frameworks indicates that the combination of consistent residue monitoring, targeted agricultural training, and stringent enforcement can significantly reduce pesticide residue levels in cucurbits and meaningfully safeguard consumer health (Calderon et al., 2022; Karimi et al., 2025). A recent study conducted in Tanzania reports findings similar to those of the present study, indicating that consumers may face various health risks associated with consuming fresh produce, as a significant proportion is contaminated with pesticides (Kapeleka and Ngowi, 2026). The findings of the present study provide a critical and locally grounded evidence base to drive such interventions, supporting the formulation of evidence-based policies, commodity-specific regulatory thresholds, and risk-oriented food safety management strategies in Tanzania.

4. Conclusion

Cucumber and watermelon samples were examined for pesticide residues and evaluated for associated health risks in Dar es Salaam. The

most frequently used pesticides were imidacloprid, thiamethoxam, acetamiprid, dimethoate, carbendazim, metalaxyl, hexaconazole, difenoconazole, and atrazine. Furthermore, the results indicated that the majority of samples were contaminated with pesticide residues at concentrations above MRLs. From a public health perspective, the detected concentrations of pesticide residues pose a potential health hazard to consumers. Based on the findings of the present study, the following measures are recommended for consideration by relevant authorities: enhanced farmer education on pre-harvest intervals and safe application practices; strengthened enforcement of existing pesticide sales regulations; and the promotion of integrated pest management strategies as alternatives to exclusive reliance on chemical control. However, the effectiveness of these interventions in reducing pesticide residues would need to be evaluated through future research.

4.1. Recommendations

1. TPHPA should conduct targeted inspections of cucumber and watermelon farms in the Pwani Region and across the entire country to verify pesticide application practices.
2. Market surveillance should be expanded to include year-round sampling.

4.2. Future research directions

1. Biomonitoring studies to measure actual pesticide exposure levels in Tanzanian children through urine or blood analysis.
2. Longitudinal studies to assess seasonal and annual trends in residue levels.
3. Intervention studies to evaluate the effectiveness of farmer training programmes in reducing residue levels.
4. Dietary exposure assessments that incorporate actual food consumption data from individual households rather than population averages.

CRedit authorship contribution statement

Alex Wenaty Ngungulu: Writing – review & editing, Visualization, Supervision, Methodology. **Bernard E Chove:** Writing – review & editing, Visualization, Supervision, Methodology. **Warren Henry Kilemire:** Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Conceptualization.

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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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.jfca.2026.109388](https://doi.org/10.1016/j.jfca.2026.109388).

Data availability

Data will be made available on request.

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