An assessment of health risks posed by consumption of pesticide residues in fruits and vegetables among residents in the Kampala Metropolitan Area in Uganda

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Abstract

Background

Pesticide use for fruits and vegetable production in Uganda may result in presence of residues on produce which may pose health risks to consumers. Uganda does not have an established system for monitoring pesticide residues in fruits and vegetables and assessing potential health risks. This research aimed to conduct a health risk assessment of presence of pesticide residues in fruits and vegetables in the Kampala Metropolitan Area in Uganda.

Method

Pesticides were measured in 160 fruits and vegetables samples collected at farms, markets, street vendors, restaurants and homes using liquid chromatography-tandem mass spectrometry and gas chromatography-mass spectrometry. Fruit and vegetable consumption information was collected from 2,177 people. Pesticide concentrations were compared with European Union maximum residual limits (MRLs). Mean values of pesticide concentration residues found in the sample of fruits and vegetables; and fruits and vegetables intake and body weight were used to calculate the estimated daily intake (EDI) of pesticide residues. EDI values were compared with acceptable daily intakes (ADI) to calculate the hazard quotient by age group, and stage at which consumption happens along the chain.

Results

Overall, 57 pesticides were detected in fruits and vegetables from farm to fork. Of the 57, 39 pesticides were detected in all the fruits and vegetables studied. Concentrations of fonofos, fenitrothion and fenhexamid were above the European Union MRLs in some samples. Hazard quotients based on dietary ingestion scenarios for eighteen pesticides, including dichlorvos (444) alanycarb (314), fonofos (68), fenitrothion (62), dioxacarb (55) and benfuracarb (24) and others, were above 1, indicating the possibility of chronic health risk to consumers. Chronic health risk decreased with age but was stable for stage at which consumption happens along the food chain. The number of pesticides with EDI greater than the ADI decreased with increase in age; with 18, 13, 9, 11, 8, 9, and 9 pesticides for age groups < 5, 5–12, 13–19, 20–25, 36–49 and ≥ 50 respectively.

Conclusion

Chronic dietary pesticide exposures to Ugandans are likely common, and for some pesticides result in exposure exceeding health-based benchmarks. Risks were highest for younger participants. There is an urgent need to increase monitoring and regulation of pesticides in fruits and vegetables in order to protect consumers, especially the children who are especially vulnerable to the adverse effects of pesticides.

Introduction

Pesticides are widely used in agriculture to control pests and disease in crops to improve the quality of produce [1]. Some commonly used classes of pesticides include organophosphates, carbamates, pyrethroids and neonicotinoids [2–5]. Most of these pesticide chemical groups, such as organophosphates, are broad spectrum insecticides, fungicides or herbicides used to control many different pests, diseases or weeds in different crops [6]. Many organophosphates, carbamates, pyrethroids and neonicotinoids, all neurotoxic pesticides, are registered for use in Uganda, [7] and use is increasing with increasing consumption of fruits and vegetables including tomatoes, cabbage and watermelons, to name but a few [8].

Organophosphates and carbamates pesticides are generally not persistent because they degrade when exposed to sunlight, air and soils, but they often have high solubility and volatility and are heavily used in many farming systems [9]. Organophosphates and carbamates inhibit cholinesterase and may impact neurodevelopment by other mechanisms, including interference in synaptogenesis and myelin sheath formation [10, 11]. Pyrethroids and neonicotinoids are often systemic pesticides with a higher affinity to soil and, especially for neonicotinoids, have the potential to bioaccumulate. They also have low volatility [12, 13]. Pyrethroids act by altering the function of voltage-gated sodium channel and consequently disrupt electrical signalling in the nervous system [14] and are generally less acutely toxic than organophosphates [15]. However, they are neurotoxicants and have been associated with confusion, lacrimation and salivation [16] and also poorer development and asthma in children [17, 18]. The mechanism of toxicity for neonicotinoids is based on selective binding and interaction with nicotinic acetylcholine receptor sites of a target organism causing paralysis that leads to death [19–21], and they have also been associated with development or neurological disorders [22] in humans.

The use of these chemicals in agriculture may result in residues in food and expose consumers. Events where high levels of pesticide contamination has occurred has resulted in acute health risks including nausea, excessive sweating and salivation, diarrhoea and vomiting, inhibition of blood clotting, and paralysis of the respiratory and circulatory systems [23]. Several studies have shown that chronic exposure to low levels of some neurotoxic pesticides are associated with poorer learning and behavioral problems in children, memory loss, loss of coordination, reduced speed of response to stimuli, reduced visual ability, altered or uncontrolled mood and general weakness; reproductive defects and cancers [24–26].

In Uganda, the volume of pesticides used has increased from 338 tonnes in the 1960s to 82,560.29 tonnes in 2019 [27]. Many farmers do not follow recommended mixing concentrations on label instructions and pre-harvest intervals [28]. Such improper pesticide use practices may result in higher levels of pesticide residues in fruits and vegetables [29] that leave the farm to the final consumer. While they are important sources of minerals, vitamins, and other healthful nutrients, consumption of fruits and vegetables contaminated with pesticide can be a route of exposure to hazardous chemicals. Fruit and vegetable consumption is a protective factor for noncommunicable diseases such as diabetes [30], and consumption is rising in among Ugandans, which consume an average 260 grams of fruits and vegetables each day [31]. Fruit and vegetable consumption has grown among residents of the Kampala Metropolitan Area (KMA) [32], and organophosphate, carbamate, pyrethroid and neonicotinoid pesticides have been previously detected in the tomatoes, watermelon, cabbages among others in this market [28, 33, 34].

In the current study, we assessed potential pesticide exposures and health risks from consumption of fruit and vegetables by residents of the KMA, in Uganda.

Materials And Methods

Study area

This study was conducted in Kampala, Wakiso and Mukono Districts, three of the 5 districts that make up the KMA in Uganda. The 3 districts have a population of 10,812,700 people [35] and cover an area of 1,000 km² [36]. Agriculture is the largest economic activity in Central Uganda within which the KMA is located, supporting 39.3% of the population [35]. This region has many large fresh produce markets, restaurants, fruit and vegetable vending along the streets, as well as many of the farms where fruits and vegetables consumed within central Uganda are grown. Kampala, Wakiso and Mukono are inhabited by 15% of Uganda's population and contain Uganda's districts that consume a large volume of the fruit and vegetables produced.

Ethical clearance to conduct the study was obtained from the Makerere University School of Public Health Higher Degrees, Research and Ethics Committee; and registered by Uganda National Council for Science and Technology (SS 5203). Participation in the study was voluntary and participants (farmers, restaurants market managers, street fruit and vegetable vendors, and household heads) provided informed written consent to collect samples and fruit and vegetable dietary intake information. All samples and questionnaire were coded with an anonymous identification number.

Pesticide residue data

Sampling of fruits and vegetables

Fruits and vegetables samples were collected from key stages along the supply chain including farms (50), markets (50), street vendors (20), restaurants (20) and homes (20), totaling 160 samples. The detailed methodology used to collect the fruits and vegetable samples has been previously described [33]. Briefly, fresh fruit and vegetable samples were purchased and collected in sterile polythene bags or PET (polyethylene terephthalate) plastic containers from selected farms, markets, and street vendors. Samples of ready-to-eat foods were bought from restaurants and homes, especially juices and salads that do not contain fat-soluble substances. Three replicate fruit and vegetable samples were collected at each location measuring at least 1 kg for larger produce as suggested by Codex guidelines [37, 38]; processed food samples were at least 1 kg or 1 litre in case of juice. The samples were stored in a cooler and transported to the laboratory within 8 hours and stored at -20°C until analysis.

Sample preparation and extraction

A total of 93 pesticides residues were screened in the fruit and vegetable samples (Supplementary Table 1). Using the Quick, Easy, Cheap, Effective, Rugged and Safe (QuEChERS) approach, samples were prepared, cleaned and extracted to determine of pesticide residues [39]. Briefly, 1–2 kgs of each sample was chopped, grinded and blended to homogenize the sample. Of the homogenized sample, 200g put into containers and immediately frozen in order to minimize the risk of degradation of any pesticide residues present. Ten grams of homogenized sample was mixed with 3g of sodium bicarbonate (NaHCO₃) and 20.0 mL ethyl acetate and centrifuged. The samples were then vortexed and placed on a mechanical shaker at 300 rpm/min for 15 minutes; 10 g of anhydrous sodium sulphate (Na₂SO₄) was then added and vortexed

and centrifuged. We filtered the crude extract using a 0.2-micron PTFE syringe filter. The final supernatant layer (0.50 g/mL) was transferred into the vials and injected into the LC-MS/MS for analysis of pesticide residues [33].

Pesticide analysis

Liquid chromatography – Tandem mass spectrometry (LC-MS/MS) analysis was carried to detect and ensure quality of the pesticides residue measurements. A zorbax eclipse plus C18 capillary column (150mm with 2.1mm internal diameter and 1.8 µm particle size) operating at 35°C to 360°C was used with the internal temperature set at 35°C for 1 minute, then ramped to 120°C per minute and 375°C per minute. This process was run over two mobile phases. Phase A involved – water (0.1% formic acid, 5 mM ammonium formate, and 2% MeOH). Phase B involved – methanol (0.1% formic acid, 5 mM ammonium formate, 2% water). The injector temperature was 120°C and carrier gas was helium at a flow rate of 13 L/minute with splitless injection. The injection volume was 5 µL at a pressure of 45 psi. The MS ion source temperature was 120°C for a minute and raised at a rate of 35°C per minute to 375°C. Confirmation analysis utilised LC-MS/MS which requires two product ions. Compounds with only one product ion were quantified and confirmed using the second ion. For confirmation, the relative ion intensity for a pesticide in a sample was calculated and the value compared to the equivalence for a calibration standard. For positive confirmation, the retention times were matched to the calibration standard as well the relative ion intensities according to the recommended maximum tolerances. Limits of detection (LOD) was determined during the method validation and measurements of uncertainty.

The method developed by Keppel et al. at the United States Food and Drug Administration (U.S. FDA) [32, 33] was used to measure dithiocarbamates (mancozeb, maneb, dithane, thiram, metam sodium and propineb. Frozen sub-samples of 10g were placed into a Duran bottle (250ml) and mixed with isooctane (20ml) followed by stannous chloride (reducing solution) in hydrochloric acid (100ml), and sealed immediately with a septum and cap. The sample was incubated at 80°C in a water bath for 1.5 hours with frequent shaking. The Duran bottles were removed and left at ambient for approximately 1 hour. The bottles were frozen for 30 minutes to allow the generated carbon disulphide gas to condense. The samples were shaken and left for 5 minutes. The organic phase (iso-octane) was removed and placed in a vial prior to the quantitation of carbon disulphide by Gas Chromatography-Mass spectrometry (GC-MS). Spiking was done twice, once at the limit of quantitation (LOQ) (50 µg/kg) and another at the expected residue level (1000 µg/kg), as obtained from previous runs during instrument optimization. A 5-point calibration was used, ranging from 0.125–5 µg/ml. The method's LOQ was set at 0.00005 mg/kg which equates to the calibration standard of 0.125 µg/ml. All extracts were analyzed using GC-MS. Final pesticide residues concentrations were expressed in mg/kg of food.

Dietary consumption data

A modified semi-structured food frequency questionnaire from the World Health Organization's (WHO) STEPwise approach to surveillance, standardized method of collecting data on risk factors for noncommunicable diseases (NCDs) [40] was used to interview 2,177 participants to assess fruit and vegetable consumption over a 24-hour dietary recall period and their body weight was concurrently measured using a weighing scale. The detailed methodology on this has been described elsewhere [31]. Briefly, based on typical Ugandan diets, a food album was developed with different quantities of selected fruits and vegetables. Each research assistant was given a copy of the food album as a guide during the interview. Respondents were asked to identify the quantities they consume per serving to determine the amounts consumed. Based on portion size in the food album, we estimated intake in grams of each fruit and vegetable each day of the week. For children under 18 years, their parents or caretakers were interviewed. Participant's weight was also measured thrice and the average calculated. For children below 2 years who cannot stand, their weight was obtained by reviewing their immunization chart or asking their parents or caregivers the measurement from their last weighing event. Socio-demographics data was also obtained using the study questionnaire. Consumption data was collected for five commonly consumed and pesticide intensive fruits and vegetables, that is: watermelon, passion fruit, tomato, cabbage and eggplant following interviews with farmers and agricultural extension workers.

Health risk assessment

We first prepared descriptive statistics of the pesticide residue levels in the produce samples. The mean pesticide concentrations were then compared with European Union maximum residual limits (EU MRLs) obtained from the pesticide residue database (<https://ec.europa.eu/food/plant/pesticides/eu-pesticides-database/mrls/?event=search.pr>) [41]. EU MRLs were used because they provided comprehensive standard values for all fruits studied; they have also been used in other African studies [42, 43]. We also used the mean pesticide concentrations to estimate pesticide intake to compare with acceptable daily intakes (ADIs). Estimated daily intake (mg/kg/bw/day) was calculated by multiplying the mean concentration of each pesticide (C) and the fruits and vegetable consumption rate (FVCR) (g/day) and dividing this by body weight (BW) using the following formula $EDI = (C \times FVCR) / BW$ [44, 45]. The FVCR used was obtained from the dietary consumption survey published in Plos One [31]. FVCR was calculated as mean consumption of fruits and vegetables studied for the sample population as well as for different age groups studied that is < 5, 5–12, 13–19, 20–24, 25–35, 36–49 and 50+. BW used was measured during the dietary consumption survey with the mean for general sample population and age groups calculated accordingly. The acceptable daily intake (ADI) (mg/kg/bw/day) for the different pesticides was obtained from the EU pesticide residue database [41]. The chronic risk assessment for pesticide residue was calculated by comparing EDI with the ADI to get the hazard quotient (HQ) using the following equation;

HQ = EDI/ADI. A hazard quotient (HQ) > 1 indicates exposures over the health-based benchmarks and the potential to induce unacceptable health risks among consumers.

Results

Pesticide residue concentrations

The mean concentration of organophosphates, carbamates, pyrethroids and neonicotinoids among other pesticides detected in watermelons, passion fruit, tomato, cabbage and eggplants and comparisons with their respective MRLs are shown in Table 1. Out of the 62 pesticide active ingredients detected, 5 were excluded due to the lack of verified maximum residue levels (MRLs) in the EU database for the studied fruits and vegetables. Therefore, 57 pesticides were considered for the risk assessment. Of the 57 pesticides, 39 pesticides were detected in all the fruits and vegetable types. Dimethoate was detected only in watermelon with a mean concentration of 0.0007 mg/kg. Fonofos was detected in all fruits and vegetables with concentrations above the MRLs in watermelon (0.03 mg/kg), passion fruit (0.02 mg/kg), cabbages (0.11 mg/kg) and eggplants (0.14 mg/kg). Methidathion was not detected in watermelon and cabbages and malathion was not detected in passion fruit. Methacrifos was detected in passion fruit at 0.00003 mg/kg and cabbages at 0.000002 mg/kg. Ethoprophos was not detected in vegetables but only in eggplants at 0.0003 mg/kg. Coumaphos and pirimiphos-methyl were detected only cabbages at 0.0000005 mg/kg and eggplants at 0.00001 mg/kg respectively. Apart from passion fruit, fenitrothion concentration was above the MRLs in watermelon (0.02 mg/kg), tomato (0.013 mg/kg), cabbage (0.03 mg/kg) and eggplant (0.03 mg/kg). Neonicotinoids were detected in almost all fruits and vegetables apart from thiacloprid that was only detected in passion fruit 0.000007 mg/kg and tomato 0.000002 mg/kg. Deltamethrin, azoxystrobin and proquinazid were only detected in vegetables with concentrations below the MRLs. Although not detected in tomato, fenhexamid's concentration was above the MRLs in watermelon (0.01 mg/kg), passion fruit (0.07 mg/kg) and cabbage (0.03 mg/kg).

Table 1
Concentration of pesticide residues per fruit and vegetable type compared with the MRLs

Pesticide residues	LOD (mg/kg)	Water melon (mg/kg)		Passion fruit (mg/kg)		Tomato (mg/kg)		Cabbage (mg/kg)		Eggplant (mg/kg)	
		Mean	MRL	Mean	MRL	Mean	MRL	Mean	MRL	Mean	MRL
Dithiocarbamate ^a	0.000006	0.001	1.5	0.00007	0.05	0.0002	3	0.0006	3	0.0004	3
Omethoate	0.00002	0.0004	0.01	0.0002	0.01	0.0003	0.01	BDL	0.01	0.00007	0.01
Acephate	0.00003	0.001	0.01	0.001	0.01	0.0001	0.01	0.00008	0.01	0.0002	0.01
Monocrotophos	0.00001	0.00003	0.01	0.00004	0.01	BDL	0.01	0.00003	0.01	0.00002	0.01
Vamidotion	0.00001	BDL	0.01	BDL	0.01	BDL	0.01	BDL	0.01	0.00008	0.01
Dimethoate	0.000008	0.0007	0.01	BDL	0.01	BDL	0.01	BDL	0.01	BDL	0.01
Mevinphos	0.00003	BDL	0.01	BDL	0.01	BDL	0.01	0.00004	0.01	0.00005	0.01
Phosphamidon	0.00002	BDL	0.01	BDL	0.01	BDL	0.01	BDL	0.01	0.00005	0.01
Fonofos	0.00001	0.03*	0.01	0.2*	0.01	0.2	10	0.1*	0.01	0.1*	0.01
Azamethiphos	0.000005	0.00002	0.01	0.000007	0.01	BDL	0.01	BDL	0.01	BDL	0.01
Dichlorvos	0.00002	0.003	0.01	0.007	0.01	0.0001	0.01	0.0002	0.01	0.0007	0.01
Malaoxon	0.00001	BDL	0.02	BDL	0.02	0.00004	0.02	0.00002	0.02	BDL	0.02
Methidathion	0.00001	BDL	0.02	0.000003	0.02	0.00002	0.02	BDL	0.02	0.000001	0.02
Malathion	0.00002	BDL	0.02	BDL	0.02	BDL	0.02	BDL	0.02	0.00007	0.02
Methacrifos	0.000005	BDL	0.01	0.00003	0.01	BDL	0.01	BDL	0.01	BDL	0.01
Ethoprophos	0.00008	BDL	0.01	BDL	0.01	BDL	0.01	BDL	0.01	BDL	0.01
Fenamiphos	0.000009	BDL	0.02	BDL	0.02	BDL	0.04	BDL	0.04	BDL	0.02
Quinalphos	0.00003	0.0001	0.01	0.0001	0.01	0.00003	0.01	BDL	0.01	0.0001	0.01
Coumaphos	0.00002	BDL	0.01	BDL	0.01	BDL	0.01	BDL	0.01	BDL	0.01
Chlorpyrifos-methyl	0.000008	BDL	0.01	0.00004	0.01	0.00009	0.01	0.00005	0.01	0.00002	0.01
Temephos	0.000008	BDL	0.01	0.00001	0.01	BDL	0.01	0.000009	0.01	BDL	0.01
Profenofos	0.00001	0.003	0.01	0.00002	0.01	0.04	10	0.003	0.01	0.005	0.01
Pirimiphosmethyl	0.00002	BDL	0.01	BDL	0.01	BDL	0.01	BDL	0.01	0.00001	0.01
Fenitrothion	0.00001	0.02*	0.01	0.004	0.01	0.01*	0.01	0.03*	0.01	0.03*	0.01
Aminocarb	0.00002	BDL	0.01	0.0007	0.01	BDL	0.01	0.00008	0.01	0.00002	0.01
Methomyl	0.00003	0.00006	0.015	0.00003	0.01	0.00003	0.01	BDL	0.01	0.00003	0.01
Aldicarbfragment	0.00001	0.00002	0.02	0.00002	0.02	0.00004	0.02	0.00002	0.02	BDL	0.02
Pirimicarb	0.00003	0.00004	0.5	0.00004	0.01	BDL	0.5	BDL	0.5	BDL	0.5
Dioxacarb	0.00001	0.004	0.01	0.003	0.01	0.003	0.01	0.003	0.01	0.004	0.01
Carbaryl	0.000008	BDL	0.01	BDL	0.01	BDL	0.01	BDL	0.01	0.00001	0.01
Carbofuran	0.000009	0.00003	0.01	BDL	0.01	BDL	0.002	BDL	0.002	0.00003	0.002
Alanycarb	0.00001	0.0001	0.02	0.00006	0.02	0.08	0.02	0.01	0.02	0.006	0.02
Benfuracarb	0.00005	0.0005	0.01	BDL	0.01	0.004	0.002	0.07	0.002	0.004	0.002
Methiocarb	0.00004	BDL	0.03	BDL	0.03	BDL	0.03	0.00005	0.03	BDL	0.03

* – above the MRLs, BDL – Below detection limits, LOD – Limit of Detection

Pesticide residues	LOD (mg/kg)	Water melon (mg/kg)		Passion fruit (mg/kg)		Tomato (mg/kg)		Cabbage (mg/kg)		Eggplant (mg/kg)	
		Mean	MRL	Mean	MRL	Mean	MRL	Mean	MRL	Mean	MRL
Imidacloprid	0.00003	0.0007	0.2	0.0008	0.05	0.0004	0.5	0.0004	0.5	0.0002	0.5
Acetamiprid	0.00002	0.004	0.2	0.002	0.01	0.008	0.5	0.005	0.4	0.001	0.2
Thiacloprid	0.00001	BDL	0.2	BDL	0.01	BDL	0.5	BDL	0.3	BDL	0.7
Bifenthrin	0.00002	0.0001	0.01	0.00004	0.01	0.0004	0.3	0.00005	0.4	BDL	0.3
Lambda-Cyhalothrin	0.00002	0.0002	0.06	0.0001	0.01	0.0002	0.07	0.0002	0.15	0.0002	0.3
Deltamethrin	0.00001	BDL	0.02	BDL	0.01	BDL	0.07	0.00006	0.1	BDL	0.4
Cypermethrin	0.00001	0.0002	0.2	BDL	0.05	0.001	0.5	0.0004	1	0.0004	0.5
Carbendazim	0.00002	BDL	0.1	0.0001	0.1	BDL	0.3	0.0001	0.1	BDL	0.5
Imazalil	0.00001	0.0005	0.01	0.0004	0.01	0.0001	0.3	0.0003	0.01	0.0003	0.01
Metazachlor	0.00001	0.00001	0.02	0.00004	0.02	0.00006	0.02	0.00002	0.4	0.00002	0.02
Metalaxyl	0.00002	BDL	0.2	BDL	0.01	0.00005	0.3	BDL	0.06	BDL	0.01
Azaconazole	0.000006	0.000009	0.01	0.0001	0.01	0.000008	0.01	0.00007	0.01	0.000008	0.01
Clomazone	0.000007	BDL	0.01	BDL	0.01	BDL	0.01	BDL	0.01	BDL	0.01
Azoxystrobin	0.000007	BDL	1	BDL	4	0.00456	3	0.003	5	0.003	3
Pyrimethanil	0.00002	0.0001	0.01	0.00008	0.01	0.0001	1	0.00008	0.01	0.00006	1
Spirotetramat	0.00002	0.00003	0.2	BDL	0.1	0.00009	2	0.00001	2	BDL	2
Fenhexamid	0.00001	0.01*	0.01	0.07*	0.01	BDL	2	0.03*	0.01	0.009	2
Fenarimol	0.00001	0.0006	0.05	0.0003	0.02	0.0002	0.02	0.0003	0.02	0.0004	0.02
Fluazifop	0.00002	0.005	0.01	BDL	0.01	BDL	0.06	0.0004	0.01	BDL	1
Flufenoxuron	0.00002	BDL	0.01	BDL	0.01	BDL	0.01	BDL	0.01	BDL	0.01
Pyriproxyfen	0.000007	BDL	0.05	BDL	0.05	BDL	1	BDL	0.05	BDL	1
Quinoxifen	0.00003	BDL	0.05	0.00005	0.02	0.00004	0.02	BDL	0.02	0.00003	0.02
Proquinazid	0.00001	BDL	0.02	BDL	0.02	0.001	0.15	0.0003	0.02	0.00009	0.02
* – above the MRLs, BDL – Below detection limits, LOD – Limit of Detection											

Health risk assessment by stage of consumption along the chain

The risk of exposures to pesticides residues in fruits and vegetables are evaluated by the stage at which consumption may occur along the chain including at the farm, market, street vendor, restaurant and home as shown in Table 2. The EDI was higher than the ADI in at least one of the stages at which consumption may occur in 16 of the 57 pesticides assessed. EDIs for dichlorvos, fenitrothion, alanycarb and benfuracarb were above the ADI at all stages of consumption. EDIs for fonofos and profenofos exceeded the ADI at four stages of consumption. Fonofos, dichlorvos, fenitrothion, dioxacarb, alanycarb and benfuracarb presented the highest risk levels with HQs of 27.5, 442.6, 23.6, 29.5, 118.0 and 23.6 respectively, at the farm and throughout the entire supply chain (See supplementary table 2). Overall, pesticide concentration at street vendors presented lower HQs and consequently lower likelihood for health risks compared to other stages along the chain (Fig. 1).

Table 2
Estimated daily intake (mg/kg/bw/day) for fruits and vegetables by stage along the chain

Pesticides	ADI (mg/kg/bw/day)	EDI (mg/kg/bw/day)				
		Farm	Market	Street	Restaurant	Home
Dithiocarbamate ^a	0.05	0.002	0.003	0.005	0.002	0.002
Omethoate	0.002	4.7E-06	0.002*	BDL	0.002*	2.9E-06
Acephate	0.03	0.005	0.004	0.0004	0.002	0.0006
Monocrotophos	0.0006	0.0001	0.0002	0.0002	0.0002	0.0001
Vamidothion	0.008	0.0002	0.0002	5.9E-07	3.54E-06	2.95E-06
Dimethoate	0.002	BDL	0.003*	BDL	BDL	BDL
Mevinphos	0.001	0.0002	0.0002	2.4E-06	2.4E-06	5.9E-05
Phosphamidon	0.0005	1.2E-06	1.18E-06	1.18E-06	BDL	1.77E-06
Fonofos	0.03	0.8*	0.9*	0.006	1.2*	0.4*
Azamethiphos	0.025	2.4E-06	5.9E-05	1.2E-06	5.9E-06	BDL
Dichlorvos	0.00008	0.04*	0.0006*	0.0004*	0.002*	0.003*
Malaoxon	0.03	4.1E-06	4.1E-06	0.0003	5.9E-05	5.9E-05
Methidathion	0.001	BDL	BDL	1.2E-06	BDL	0.0002
Malathion	0.03	0.0003	BDL	BDL	BDL	2.9E-06
Methacrifos	0.006	BDL	0.0001	BDL	BDL	BDL
Ethoprophos	0.0004	BDL	0.0001	BDL	0.0001	0.0002
Fenamiphos	0.0008	5.9E-08	1.2E-06	5.9E-05	1.8E-06	BDL
Quinalphos	0.001	0.0001	0.0005	0.0004	0.001*	0.0006
Coumaphos	0.001	1.8E-07	BDL	BDL	BDL	BDL
Chlorpyrifos-methyl	0.01	0.0005	BDL	2.9E-06	0.0006	BDL
Temephos	0.001	BDL	3.5E-06	BDL	2.9E-06	0.0001
Profenofos	0.03	0.1*	0.04*	0.04*	0.06*	0.004
Pirimiphosmethyl	0.03	BDL	4.7E-06	BDL	BDL	BDL
Fenitrothion	0.005	0.1*	0.05*	0.2*	0.2*	0.02*
Aminocarb	0.001	0.0002	0.003*	0.0001	0.0001	5.9E-05
Methomyl	0.0025	0.0002	0.0003	4.1E-06	0.0002	2.9E-06
Aldicarbfragment	0.001	0.0001	0.0001	0.000177	5.9E-05	0.0001
Pirimicarb	0.035	0.0001	0.0001	BDL	0.0004	5.9E-05
Dioxacarb	0.001	0.03*	0.02*	0.02*	BDL	BDL
Carbaryl	0.0075	2.4E-06	2.4E-06	1.8E-06	BDL	0.0001
Carbofuran	0.00015	4.1E-06	5.9E-07	0.0003*	0.0002*	2.9E-07
Alanycarb	0.001	0.1*	0.1*	0.06*	0.1*	0.2*
Benfuracarb	0.01	0.2*	0.05*	0.02*	4.7E-13	0.02*
Methiocarb	0.00025	0.0002	5.9E-05	0.0002	4.1E-06	5.9E-07
Imidacloprid	0.06	0.003	0.002	0.005	0.006	0.001

BDL – Below detection limit, ADI – Acceptable Daily Intake, EDI – Estimated Daily Intake * - EDI greater than ADI (HQ > 1)

Pesticides	ADI (mg/kg/bw/day)	EDI (mg/kg/bw/day)				
		Farm	Market	Street	Restaurant	Home
Acetamiprid	0.025	0.04*	0.02	0.01	0.01	0.005
Thiacloprid	0.01	3.5E-06	BDL	BDL	BDL	BDL
Bifenthrin	0.015	0.0006	0.002	4.7E-06	0.0002	2.4E-06
Lambda-Cyhalothrin	0.0012	0.001	0.001	0.001	0.0006	0.0006
Deltamethrin	0.01	2.4E-06	0.0002	BDL	BDL	BDL
Cypermethrin	0.0016	0.004*	0.002*	0.005*	0.001	0.0006
Carbendazim	0.02	1.2E-06	0.001	2.4E-06	5.9E-05	4.7E-07
Imazalil	0.025	0.002	0.001	0.004	0.002	0.002
Metazachlor	0.08	0.0002	0.0002	0.0002	0.0002	0.0001
Metalaxyl	0.08	1.2E-06	0.0002	BDL	BDL	BDL
Azaconazole	0.001	4.7E-06	0.0005	0.0004	BDL	0.0006
Clomazone	0.133	1.2E-06	BDL	BDL	BDL	BDL
Azoxystrobin	0.2	0.02	BDL	BDL	0.01	0.04
Pyrimethanil	0.17	0.0002	0.0006	0.001	0.0005	0.0006
Spirotetramat	0.05	0.0003	0.0002	0.0002	2.9E-06	0.0001
Fenhexamid	0.2	0.1	0.2	0.6*	0.006	0.05
Fenarimol	0.01	0.002	0.0006	0.002	0.002	0.005
Fluazifop	0.004	0.0006	0.02*	BDL	BDL	BDL
Flufenoxuron	0.01	1.8E-06	2.4E-06	1.8E-07	1.2E-06	4.1E-07
Pyriproxyfen	0.05	BDL	BDL	2.9E-06	BDL	BDL
Quinoxifen	0.2	0.0002	5.9E-05	0.0003	1.2E-06	0.0003
Proquinazid	0.01	0.003	0.0006	0.002	0.001	BDL
BDL – Below detection limit, ADI – Acceptable Daily Intake, EDI – Estimated Daily Intake * - EDI greater than ADI (HQ > 1)						

Health risk assessment by age group

We evaluated the risk of consumption of pesticide residues by age of consumers as shown in Table 3. EDIs for fonofos, dichlorvos, profenofos, fenitrothion, dioxacarb, alanycarb, benfuracarb, cypermethrin and fluazifop exceeded ADIs throughout all age groups and consequently pose chronic health risks. The number of pesticides with EDIs greater than the ADI decreased with age with 18, 13, 9, 11, 8, 9, and 9 for age groups under 5 years, 5–12, 13–19, 20–25, 36–49 and 50 + years respectively. Dichlorvos had the highest risk with a HQ of 444 followed by alanycarb (314), Fonofos (68), fenitrothion (62), dioxacarb (55) and benfuracarb (24) among children under 5 with a similar trend across age groups (see supplementary table 2). Overall, HQ values decreased across age groups with children under 5 presenting highest risks and adults 50 + having the lowest chronic health risks for the nine pesticides as shown in Fig. 2.

Table 3
Estimated daily intake (mg/kg/bw/day) for fruits and vegetables by age group

Pesticides	ADI (mg/kg bw/day)	EDI (mg/kg/bw/day)							
		General population	< 5	5–12	13–19	20–24	25–35	36–49	50+
Dithiocarbamate ^a	0.05	0.003	0.007	0.004	0.002	0.003	0.002	0.002	0.002
Omethoate	0.002	0.001	0.003*	0.002	0.001	0.001	0.001	0.001	0.001
Acephate	0.03	0.003	0.008	0.005	0.003	0.003	0.003	0.002	0.003
Monocrotophos	0.0006	0.0002	0.0005	0.0003	0.0004	0.0002	0.0002	0.0001	0.0002
Vamidothion	0.008	0.0001	0.0003	0.0002	0.0001	0.0001	0.0001	9.4E-05	0.0001
Dimethoate	0.002	0.0008	0.002*	0.001	0.0008	0.0009	0.0008	0.0007	0.0007
Mevinphos	0.001	0.0001	0.0003	0.0002	0.0001	0.0001	0.0001	9.4E-05	0.0001
Phosphamidon	0.0005	5.9E-06	1.7E-05	9.4E-06	5.8E-06	6.7E-06	5.4E-06	4.7E-06	5.1E-06
Fonofos	0.03	0.7*	2.0*	1.2*	0.7*	0.8*	0.8*	0.6*	0.6*
Azamethiphos	0.025	4.1E-05	0.0001	6.6E-05	4.1E-05	4.7E-05	3.8E-05	3.3E-05	3.5E-05
Dichlorvos	0.00008	0.01*	0.04*	0.02*	0.01*	0.01*	0.01*	0.01*	0.01*
Malaoxon	0.03	5.9E-05	0.0002	9.4E-05	5.8E-05	6.7E-05	5.4E-05	4.7E-05	5.1E-05
Methidathion	0.001	3.0E-05	8.2E-05	4.7E-05	2.9E-05	3.3E-05	2.7E-05	2.3E-05	2.5E-05
Malathion	0.03	0.0001	0.0003	0.0002	0.0001	0.0001	0.0001	9.4E-05	0.0001
Methacrifos	0.006	4.1E-05	0.0001	6.6E-05	4.1E-05	4.7E-05	3.8E-05	3.3E-05	3.5E-05
Ethoprophos	0.0004	5.9E-05	0.0002	9.4E-05	5.8E-05	6.7E-05	5.4E-05	4.7E-05	5.1E-05
Fenamiphos	0.0008	1.2E-05	3.3E-05	1.9E-05	1.2E-05	1.3E-05	1.1E-05	9.4E-06	1.0E-05
Quinalphos	0.001	0.0005	0.001*	0.0008	0.0005	0.0005	0.0004	0.0004	0.0004
Coumaphos	0.001	5.3E-07	1.5E-06	8.4E-07	5.2E-07	6.0E-07	4.9E-07	4.2E-07	4.5E-07
Chlorpyrifos-methyl	0.01	0.0002	0.0007	0.0004	0.0002	0.0003	0.0002	0.0002	0.0002
Temephos	0.001	3.0E-05	8.2E-05	4.7E-05	2.9E-05	3.3E-05	2.7E-05	2.3E-05	2.5E-05
Profenofos	0.03	0.06*	0.2*	0.1*	0.06*	0.07*	0.06*	0.05*	0.05*
Pirimiphosmethyl	0.03	1.8E-05	4.9E-05	2.8E-05	1.7E-05	2E-05	1.6E-05	1.4E-05	1.5E-05
Fenitrothion	0.005	0.1*	0.3*	0.2*	0.1*	0.1*	0.1*	0.09*	0.1*
Aminocarb	0.001	0.0009	0.003*	0.002*	0.0009	0.001*	0.0009	0.0007	0.0008
Methomyl	0.0025	0.0002	0.0005	0.0003	0.0002	0.0002	0.0002	0.0001	0.0001
Aldicarbfragment	0.001	0.0001	0.0003	0.0002	0.0001	0.0001	0.0001	9.4E-05	0.0001

BDL – Below detection limit, ADI – Acceptable Daily Intake, EDI – Estimated Daily Intake * - EDI greater than ADI (HQ > 1)

Pesticides	ADI (mg/kg bw/day)	EDI (mgkg/bw/day)							
		General population	< 5	5–12	13–19	20–24	25–35	36–49	50+
Pirimicarb	0.035	0.0001	0.0003	0.0002	0.0001	0.0001	0.0001	9.4E-05	0.0001
Dioxacarb	0.001	0.02*	0.06*	0.03*	0.02*	0.02*	0.02*	0.02*	0.02*
Carbaryl	0.0075	3.0E-05	8.2E-05	4.7E-05	2.9E-05	3.3E-05	2.7E-05	2.3E-05	2.5E-05
Carbofuran	0.00015	5.9E-05	0.0002*	9.4E-05	5.8E-05	6.7E-05	5.4E-05	4.7E-05	5.1E-05
Alanycarb	0.001	0.1*	0.3*	0.2*	0.1*	0.1*	0.1*	0.09*	0.1*
Benfuracarb	0.01	0.09*	0.2*	0.1*	0.09*	0.1*	0.08*	0.07*	0.08*
Methiocarb	0.00025	0.0001	0.0003*	0.0002	0.0001	0.0001	0.0001	9.4E-05	0.0001
Imidacloprid	0.06	0.003	0.008	0.005	0.003	0.003	0.003	0.002	0.003
Acetamiprid	0.025	0.02	0.06*	0.04*	0.02	0.03*	0.02	0.02	0.02
Thiacloprid	0.01	1.2E-05	3.3E-05	1.9E-05	1.2E-05	1.3E-05	1.1E-05	9.4E-06	1.0E-05
Bifenthrin	0.015	0.0007	0.0015	0.001	0.0007	0.0008	0.0007	0.0006	0.0006
Lambda-Cyhalothrin	0.0012	0.001	0.003*	0.002*	0.001	0.001	0.0009	0.0008	0.0009
Deltamethrin	0.01	5.9E-05	0.0002	9.4E-05	5.8E-05	6.7E-05	5.4E-05	4.7E-05	5.1E-05
Cypermethrin	0.0016	0.003*	0.008*	0.004*	0.003*	0.003*	0.002*	0.002*	0.002*
Carbendazim	0.02	0.0003	0.0008	0.0005	0.0003	0.0003	0.0003	0.0002	0.0003
Imazalil	0.025	0.002	0.005	0.003	0.002	0.002	0.002	0.002	0.002
Metazachlor	0.08	0.0002	0.0005	0.0003	0.0002	0.0002	0.0002	0.0001	0.0002
Metalaxyl	0.08	5.9E-05	0.0002	9.4E-05	5.8E-05	6.7E-05	5.4E-05	4.7E-05	5.1E-05
Azaconazole	0.001	0.0002	0.0007	0.0004	0.0002	0.0003	0.0002	0.0002	0.0002
Clomazone	0.133	3.5E-06	9.9E-06	5.6E-06	3.5E-06	4E-06	3.3E-06	2.8E-06	3.0E-06
Azoxystrobin	0.2	0.01	0.04	0.02	0.01	0.01	0.01	0.01	0.01
Pyrimethanil	0.17	0.0006	0.002	0.0009	0.0006	0.0007	0.0005	0.0005	0.0005
Spirotetramat	0.05	0.0002	0.0005	0.0003	0.0002	0.0002	0.0002	0.0001	0.0002
Fenhexamid	0.2	0.1	0.4*	0.2*	0.1	0.2	0.1	0.1	0.1
Fenarimol	0.01	0.002	0.006	0.003	0.002	0.002	0.002	0.002	0.002
Fluazifop	0.004	0.007*	0.02*	0.01*	0.007*	0.008*	0.006*	0.006*	0.006*
Flufenoxuron	0.01	1.8E-05	4.9E-05	2.8E-05	1.7E-05	2E-05	1.6E-05	1.4E-05	1.5E-05
Pyriproxyfen	0.05	3.5E-06	9.9E-06	5.6E-06	3.5E-06	4E-06	3.3E-06	2.8E-06	3.0E-06
Quinoxifen	0.2	0.0002	0.0005	0.0003	0.0002	0.0002	0.0002	0.0001	0.0002
Proquinazid	0.01	0.002	0.005	0.003	0.002	0.002	0.002	0.001	0.001
BDL – Below detection limit, ADI – Acceptable Daily Intake, EDI – Estimated Daily Intake * - EDI greater than ADI (HQ > 1)									

Discussion

Pesticides were detected in all studied fruits and vegetables, with 39 active ingredients (AIs) detected in all samples and 18 AIs in at least some of the food samples. Fonofos, fenitrothion and fenhexamid concentrations were above the MRLs in watermelon, passion fruit, tomato, cabbage and eggplant. Risk assessment calculations show that EDIs for 18 pesticides were above the ADI in some cases, with HQs that ranged from 1 up to 443 and thus may pose chronic health risks. Children experienced the highest HQs and therefore potentially higher chronic health risks from pesticide residues in fruits and vegetables.

Overall, 29% of the pesticides we tested for had EDIs over an ADI. This is a high proportion of exceedances compared to other risk assessment studies [46–48]. When calculated by stage along the supply chain and age group, 16 and 18 pesticides respectively had high EDIs above their ADI. As discussed by JA Vaccaro and FG Huffman [49], age is a key dietary risk factor that should be considered while performing health risk assessment. Several fruit and vegetable surveillance studies have estimated EDI and similar EDIs. Studies in Chile, Poland and Kazakhstan had EDIs ranging from < 0.001 to 5.2 [47, 50–54], which is within the range of our findings.

Many pesticides were detected in all studied fruits and vegetables with levels below the EU MRLs except for Fonofos, fenitrothion and fenhexamid. Our findings are consistent with existing literature showing detection of many pesticides in fruits and vegetables [50, 51, 55, 56]. Like our findings, many past studies have pesticide residue levels that are above MRL values, especially organophosphates like fenitrothion [46, 48, 53, 54, 57–60]. For example, recent studies in Ghana and Nigeria also found that many pesticides residue levels in produce were above the respective MRLs [42, 61]. The most frequently detected pesticides that have exceeded MRLs have been organophosphates, carbamates, pyrethroids and neonicotinoids based on studies in Uganda, Ghana, Egypt, Poland and Chile [4, 5, 28, 34, 42, 43, 46, 62], especially in leafy vegetables [50, 51]. Given that MRLs are determined based on good agricultural practices (GAPs) in field experiments and not necessarily health risks [63, 64], consumption of pesticides below the MRLs might exceed health-based exposure benchmarks depending on individual consumption patterns.

Our findings confirm similar findings to other studies carried out in Poland, Nigeria and Saudi Arabia which found that many pesticides had a HQ > 1 [46, 65, 66]. On the other hand, literature from Turkey, Poland, Ghana, China and South Korea showed no chronic health risk associated with pesticide residues in fruits and vegetables [53, 54, 58, 60, 67–70]. Using probabilistic modelling, Z Eslami, V Mahdavi and B Tajdar-Oranj [57] in Iran found that pesticide residues did not pose health risks to adults and children. When assessed by stage along the supply chain, some pesticide showed a low HQ and consequently lower risk when consumed at farm than at other stages further along the supply chain, such as restaurants and homes. Our findings are similar to those from previous studies which have shown a higher chronic health risk for stages upstream along the chain [62, 71]. When HQ was assessed by age, children more frequently experienced higher hazard quotients (18 – 13) compared with adults (11 – 9) with HQs up to 443, compared with a maximum HQ for adults at XX. Our findings are similar to findings from studies from Chile, Nigeria and China that assessed risk by age which found that chronic health risks were higher in children compared to adults [50, 53, 69, 72].

Our findings have implications on policy and future research. We used the EU MRLs and ADIs to evaluate exposures and risks, these benchmarks are lower and hence more sensitive than other guidelines. For example, Codex Alimentarius guidelines are higher, which would suggest lower health risks based on the exposure we evaluated. There is a need to develop Ugandan standards for MRLs and ADI based on local studies and context. The high HQs demonstrate in our study also demonstrate the need for routine monitoring and surveillance of pesticide residues in foods, especially in fruits and vegetables.

This study has several strengths and limitations. This study is the largest in Uganda to examine pesticide residues in fruits and vegetables; and we interviewed over 2000 residents to obtain information on dietary intake patterns. Dietary consumption data for fruit and vegetable was measured using a contextualised food album and thus presents a true reflection of the study community. We used mean residue concentrations to assess likely average exposures to consumers, but individual variability in eating patterns may result in higher or lower chronic exposures [73]. Additionally, we computed hazard quotients for consumption of individual foods. It is likely that consumers ate several different fruits or vegetables on any given day. In future analyses, we will use probabilistic methods to assess the range of potential exposures and health risks from more realistic diet patterns. We will also apply relative potency factors (RPFs) to assess cumulative health risks for pesticide classes with established RPFs [74]. Fruits and vegetables were not tracked from farm to fork during sampling due to cost and time challenges. Future studies examining pesticide residues along the farm to fork chain should track and sample individual produce lots from harvest to the consumer. Additionally, this study was carried out in a primarily urban community and may not represent a typical Ugandan rural setting. Finally, dietary consumption measurement did not cover the broad spectrum of fruits and vegetables but rather focussed on commonly consumed items within the study area (watermelon, passion fruit, tomato, cabbage and eggplant). However, the study area represents a large proportion of the Ugandan population and several commonly eaten foods.

Conclusion

Sixty-two (62) pesticide residues were detected in fruits and vegetables from farm to fork. Concentrations of fonofos, fenitrothion and fenhexamid were above EU MRLs in watermelon, passion fruit, tomato, cabbages and eggplant. Exposures to sixteen and eighteen pesticides exceeded health-based benchmarks and potentially pose chronic health risks to consumers, especially to children. The study findings demonstrate the urgent need for routine pesticide monitoring and surveillance and risk assessment for fruits and vegetables in local Ugandan markets. There is also need to regulate the levels of pesticide in fruits and vegetables in order to protect consumers, especially the children who present higher chronic health risks.

Abbreviations

ADI	Acceptable Daily Intake
Als	Active Ingredients
BDL	Below Detection Limits
BW	Body Weight
C	Mean concentration of each Pesticide
EDI	Estimated Daily Intake
EU MRLs	European Union Maximum Residual Limits
FVCR	Fruit and Vegetable Intake Rate
GAPs	Good Agricultural Practices
GC – MS	Gas Chromatography – Mass Spectrometry
HQ	Hazard Quotient
KMA	Kampala Metropolitan Area
LC – MS/MS	Liquid Chromatography – Tandem Mass Spectrometry
LOD	Limit of Detection
LOQ	Limit of Quantification
MRLs	Maximum Residual Limits
NCDs	Noncommunicable Diseases
QuEChERS	Quick, Easy, Cheap, Effective, Rugged and Safe
RPFs	Relative Potency Factors
U.S. FDA	United States Food and Drugs Authority
WHO	World Health Organisation

Declarations

Ethics approval and consent to participate

Ethical approval was granted by the Makerere University School of Public Health Higher Degrees, Research and Ethics Committee (HDREC); and registered by Uganda National Council for Science and Technology (SS 5203). All participants provided written informed consent before their involvement in the study.

Consent for publication

Not applicable

Availability of data and material

The dataset used during the study is available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contribution

CS: conceived of the study; participated in the design, coordination, and implementation of all study field activities; conducted the statistical analysis; and drafted the manuscript; AB: conceived of the study; participated in the design, and helped to draft the manuscript; JCS: conceived of the study; participated in the design, and helped to draft the manuscript; FS: participated in the design, and helped to draft the manuscript; DG: conceived of the study; participated in the design, and helped to draft the manuscript. All authors read and approved the final manuscript.

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References

1. Aktar MW, Sengupta D, Chowdhury A: **Impact of pesticides use in agriculture: their benefits and hazards.** *Interdisciplinary Toxicology* 2009, **2**(1):1-12.
2. Matowo NS, Tanner M, Munhenga G, Mapua SA, Finda M, Utzinger J, Ngowi V, Okumu FO: **Patterns of pesticide usage in agriculture in rural Tanzania call for integrating agricultural and public health practices in managing insecticide-resistance in malaria vectors.** *Malaria Journal* 2020, **19**(1):257.
3. Maggi F, Tang FHM, la Cecilia D, McBratney A: **PEST-CHEMGRIDS, global gridded maps of the top 20 crop-specific pesticide application rates from 2015 to 2025.** *Scientific Data* 2019, **6**(1):170.
4. Fuhrmann S, Farnham A, Staudacher P, Atuhaire A, Manfioletti T, Niwagaba CB, Namirembe S, Mugweri J, Winkler MS, Portengen L *et al.*: **Exposure to multiple pesticides and neurobehavioral outcomes among smallholder farmers in Uganda.** *Environment international* 2021, **152**:106477.
5. Staudacher P, Fuhrmann S, Farnham A, Mora AM, Atuhaire A, Niwagaba C, Stamm C, Eggen RI, Winkler MS: **Comparative Analysis of Pesticide Use Determinants Among Smallholder Farmers From Costa Rica and Uganda.** *Environmental health insights* 2020, **14**:1178630220972417.
6. Hill MP, Macfadyen S, Nash MA: **Broad spectrum pesticide application alters natural enemy communities and may facilitate secondary pest outbreaks.** *PeerJ* 2017, **5**:e4179-e4179.
7. Ministry of Agriculture Animal Industry and Fisheries: **Register of agricultural chemical registered under section 4 of the agricultural chemicals (control) act, 2006 at 6th April 2018.** In: *Register of agricultural chemical registered under section 4 of the agricultural chemicals (control) act, 2006.* Edited by Fisheries MoAAla. Entebbe: Ministry of Agriculture Animal Industry and Fisheries; 2018.
8. Ngabirano H, Birungi G: **Pesticide use in vegetable production in rural Uganda -A case study of Kabale District, South western Uganda.** *African Journal of Agricultural Research* 2020, **16**(11):1573-1581.

9. Akkad R, Schwack W: **Multi-enzyme inhibition assay for the detection of insecticidal organophosphates and carbamates by high-performance thin-layer chromatography applied to determine enzyme inhibition factors and residues in juice and water samples.** *Journal of chromatography B, Analytical technologies in the biomedical and life sciences* 2010, **878**(17-18):1337-1345.
10. Vale A, Lotti M: **Organophosphorus and carbamate insecticide poisoning.** *Handbook of clinical neurology* 2015, **131**:149-168.
11. Sagiv SK, Bruno JL, Baker JM, Palzes V, Kogut K, Rauch S, Gunier R, Mora AM, Reiss AL, Eskenazi B: **Prenatal exposure to organophosphate pesticides and functional neuroimaging in adolescents living in proximity to pesticide application.** *Proceedings of the National Academy of Sciences* 2019, **116**(37):18347-18356.
12. Laskowski D.A.: **Physical and Chemical Properties of Pyrethroids.** In: *Reviews of environmental contamination and toxicology. Volume 174*, edn. Edited by G.W. W. New York, NY: Springer; 2002.
13. Bonmatin JM, Giorio C, Girolami V, Goulson D, Kreutzweiser DP, Krupke C, Liess M, Long E, Marzaro M, Mitchell EAD *et al*: **Environmental fate and exposure; neonicotinoids and fipronil.** *Environmental science and pollution research international* 2015, **22**(1):35-67.
14. Soderlund DM: **Chapter 77 - Toxicology and Mode of Action of Pyrethroid Insecticides.** In: *Hayes' Handbook of Pesticide Toxicology (Third Edition)*. edn. Edited by Krieger R. New York: Academic Press; 2010: 1665-1686.
15. Simaremare SRS, Hung C-C, Hsieh C-J, Yiin L-M: **Relationship between Organophosphate and Pyrethroid Insecticides in Blood and Their Metabolites in Urine: A Pilot Study.** *International journal of environmental research and public health* 2019, **17**(1):34.
16. Bradberry SM, Cage SA, Proudfoot AT, Vale JA: **Poisoning due to pyrethroids.** *Toxicological reviews* 2005, **24**(2):93-106.
17. Pitzer EM, Williams MT, Vorhees CV: **Effects of pyrethroids on brain development and behavior: Deltamethrin.** *Neurotoxicology and Teratology* 2021, **87**:106983.
18. Vester AI, Chen M, Marsit CJ, Caudle WM: **A Neurodevelopmental Model of Combined Pyrethroid and Chronic Stress Exposure.** *Toxics* 2019, **7**(2):24.
19. Taillebois E, Cartereau A, Jones AK, Thany SH: **Neonicotinoid insecticides mode of action on insect nicotinic acetylcholine receptors using binding studies.** *Pesticide Biochemistry and Physiology* 2018, **151**:59-66.
20. Cartereau A, Taillebois E, Le Questel JY, Thany SH: **Mode of Action of Neonicotinoid Insecticides Imidacloprid and Thiacloprid to the Cockroach Parnas7 Nicotinic Acetylcholine Receptor.** *Int J Mol Sci* 2021, **22**(18).
21. Houchat J-N, Cartereau A, Le Mauff A, Taillebois E, Thany SH: **An Overview on the Effect of Neonicotinoid Insecticides on Mammalian Cholinergic Functions through the Activation of Neuronal Nicotinic Acetylcholine Receptors.** *Int J Environ Res Public Health* 2020, **17**(9):3222.
22. Cimino AM, Boyles AL, Thayer KA, Perry MJ: **Effects of Neonicotinoid Pesticide Exposure on Human Health: A Systematic Review.** *Environmental health perspectives* 2017, **125**(2):155-162.
23. PAN: **Hazardous pesticide and health impacts in Africa.** In: *Food and fairness briefing No 6*. vol. 6. United Kingdom: PAN UK; 2018.
24. Nicolopoulou-Stamati P, Maipas S, Kotampasi C, Stamatis P, Hens L: **Chemical Pesticides and Human Health: The Urgent Need for a New Concept in Agriculture.** *Frontiers in Public Health* 2016, **4**:148.
25. Coker E, Chevrier J, Rauch S, Bradman A, Obida M, Crause M, Bornman R, Eskenazi B: **Association between prenatal exposure to multiple insecticides and child body weight and body composition in the VHEMBE South African birth cohort.** *Environment international* 2018, **113**:122-132.
26. Chiu YH, Williams PL, Gillman MW, Gaskins AJ, Minguez-Alarcon L, Souter I, Toth TL, Ford JB, Hauser R, Chavarro JE: **Association Between Pesticide Residue Intake From Consumption of Fruits and Vegetables and Pregnancy Outcomes Among Women Undergoing Infertility Treatment With Assisted Reproductive Technology.** *JAMA internal medicine* 2018, **178**(1):17-26.
27. FOA: **FAOSTAT: The State of Food Security Indicators (Food Security and Nutrition).** In., August 20, 2021 edn. Rome: Food and Agricultural Organisation; 2021.
28. Kaye E, Nyombi A, Mutambuze IL, Muwesa R: **Mancozeb Residue on Tomatoes in Central Uganda.** *Journal of Health and Pollution* 2015, **5**(8):1-6.
29. Grewel AS, Singla A, Kamboj P, Dua JS: **Pesticide Residues in Food Grains, Vegetables and Fruits: A Hazard to Human Health.** *Journal of Medicinal Chemistry and Toxicology* 2017, **2**(1):40-46.
30. World Health Organisation: **Global Action Plan for the Prevention and Control of NCDs 2013-2020.** In. Geneva: Switzerland World Health Organisation; 2013: 103.
31. Ssemugabo C, Ssempebwa J, Bradman A, Sille F, Guwatudde D: **Fruits and vegetables consumption in Kampala Metropolitan Area, Uganda: a household survey** In. Edited by University M. Kampala: Uganda; 2021: 16.
32. Kabwama SN, Bahendeka SK, Wesonga R, Mutungi G, Guwatudde DJAoPH: **Low consumption of fruits and vegetables among adults in Uganda: findings from a countrywide cross-sectional survey.** *Archives of Public Health* 2019, **77**(1):4.

33. Ssemugabo C, Bradman A, Ssempebwa JC, Sillé F, Guwatudde D: **Pesticide residues in fresh fruit and vegetables from farm to fork in the Kampala Metropolitan Area, Uganda** In: *Food Additives and Contaminants Part B*. Edited by University M; 2021.
34. Atuhaire A, Kaye E, Mutambuza IL, Matthews G, Friedrich T, Jørs E: **Assessment of Dithiocarbamate Residues on Tomatoes Conventionally Grown in Uganda and the Effect of Simple Washing to Reduce Exposure Risk to Consumers**. *Environmental health insights* 2017, **11**:1178630217712218.
35. UBOS: **Uganda Bureau of Statistics's Statistical Abstract 2018**. In. Kampala: Uganda Bureau of Statistics 2018.
36. Kasimbazi E: **Urban Expansion in the Greater Kampala Metropolitan Area, Uganda**. In. Nairobi: UN Habitat 2016.
37. El-Zaher TR, Nasr IN, Mahmoud HA: **Behavior of Some Pesticide residues in and on Tomato and Kidney Beans Fruits Grown in Open Field**. *American-Eurasian Journal of Toxicological Sciences* 2011, **3**(3):213-218.
38. Food and Agriculture Organisation: **Recommended methods of sampling for pesticide residues for the determination of compliance with MRLs**. Rome: Food and agriculture Organisation of United Nations; 1999.
39. Anastassiades M, Lehota S, Štajnbaher D: **Quick, easy, cheap, effective, rugged, and safe (QuEChERS) approach for the determination of pesticide residues**; 2002.
40. WHO: **The WHO STEPwise approach to noncommunicable disease risk factor surveillance (STEPS)**. In. Geneva: World Health organisation; 2017.
41. **Pesticide residues** [<https://ec.europa.eu/food/plant/pesticides/eu-pesticides-database/mrls/?event=search.pr>]
42. Fosu PO, Donkor A, Ziwu C, Dubey B, Kingsford-Adaboh R, Asante I, Nyarko S, Tawiah R, Nazzah N: **Surveillance of pesticide residues in fruits and vegetables from Accra Metropolis markets, Ghana, 2010–2012: a case study in Sub-Saharan Africa**. *Environmental Science Pollution Research* 2017, **24**(20):17187-17205.
43. Issa AB, Yassin K, Loutfy N, Ahmed MT: **Risk assessment of some organic contaminants: a case study based on food consumption in Tanta and Ismailia cities, Egypt**. *Environmental science and pollution research international* 2018, **25**(34):34212-34220.
44. Gad Alla SA, Loutfy NM, Shendy AH, Ahmed MT: **Hazard index, a tool for a long term risk assessment of pesticide residues in some commodities, a pilot study**. *Regulatory Toxicology and Pharmacology* 2015, **73**(3):985-991.
45. Chen C, Qian Y, Chen Q, Tao C, Li C, Li Y: **Evaluation of pesticide residues in fruits and vegetables from Xiamen, China**. *Food Control* 2011, **22**(7):1114-1120.
46. Szpyrka E, Kurdziel A, Słowik-Borowiec M, Grzegorzak M, Matyaszek A: **Consumer exposure to pesticide residues in apples from the region of south-eastern Poland**. *Environ Monit Assess* 2013, **185**(11):8873-8878.
47. Lozowicka B, Abzeitova E, Sagitov A, Kaczynski P, Toleubayev K, Li A: **Studies of pesticide residues in tomatoes and cucumbers from Kazakhstan and the associated health risks**. *Environ Monit Assess* 2015, **187**(10):609.
48. Mebdoua S, Lazali M, Ounane SM, Tellah S, Nabi F, Ounane G: **Evaluation of pesticide residues in fruits and vegetables from Algeria**. *Food additives & contaminants Part B, Surveillance* 2017, **10**(2):91-98.
49. Vaccaro JA, Huffman FG: **Dietary Risk Factors by Race/Ethnicity, Age-Group, and Gender in a Representative Sample of US Older Adults**. *The journal of nutrition, health & aging* 2017, **21**(6):704-709.
50. Elgueta S, Valenzuela M, Fuentes M, Meza P, Manzur JP, Liu S, Zhao G, Correa A: **Pesticide Residues and Health Risk Assessment in Tomatoes and Lettuces from Farms of Metropolitan Region Chile**. *Molecules (Basel, Switzerland)* 2020, **25**(2).
51. Elgueta S, Fuentes M, Valenzuela M, Zhao G, Liu S, Lu H, Correa A: **Pesticide residues in ready-to-eat leafy vegetables from markets of Santiago, Chile, and consumer's risk**. *Food Additives & Contaminants: Part B* 2019, **12**(4):259-267.
52. Elgueta S, Moyano S, Sepúlveda P, Quiroz C, Correa A: **Pesticide residues in leafy vegetables and human health risk assessment in North Central agricultural areas of Chile**. *Food additives & contaminants Part B, Surveillance* 2017, **10**(2):105-112.
53. Si WS, Wang SY, Zhang YD, Kong C, Bai B: **Pesticides and risk assessment in Shanghai fruit and raw eaten vegetables**. *Food additives & contaminants Part B, Surveillance* 2021:1-11.
54. Szpyrka E, Słowik-Borowiec M: **Consumer health risk to pesticide residues in Salvia officinalis L. and its infusions**. *Journal of environmental science and health Part B, Pesticides, food contaminants, and agricultural wastes* 2019, **54**(1):14-19.
55. Jallow MFA, Awadh DG, Albaho MS, Devi VY, Ahmad N: **Monitoring of Pesticide Residues in Commonly Used Fruits and Vegetables in Kuwait**. *International Journal of Environmental Research and Public Health* 2017, **14**(8):833.
56. López-Dávila E, Houbraken M, De Rop J, Claus G, Wumbei A, Romero Romero O, Spanoghe P: **Pesticide traces in local crops of Sancti Spiritus, Cuba: risk assessment study**. *International Journal of Food Contamination* 2021, **8**(1):1.
57. Eslami Z, Mahdavi V, Tajdar-Oranj B: **Probabilistic health risk assessment based on Monte Carlo simulation for pesticide residues in date fruits of Iran**. *Environmental science and pollution research international* 2021, **28**(31):42037-42050.

58. Kazar Soydan D, Turgut N, Yalçın M, Turgut C, Karakuş PBK: **Evaluation of pesticide residues in fruits and vegetables from the Aegean region of Turkey and assessment of risk to consumers.** *Environmental science and pollution research international* 2021, **28**(22):27511-27519.
59. Toptancı İ, Kiralan M, Ramadan MF: **Levels of pesticide residues in fruits and vegetables in the Turkish domestic markets.** *Environmental science and pollution research international* 2021, **28**(29):39451-39457.
60. Akoto O, Gavor S, Appah MK, Apau J: **Estimation of human health risk associated with the consumption of pesticide-contaminated vegetables from Kumasi, Ghana.** *Environ Monit Assess* 2015, **187**(5):244.
61. Adeleye AO, Sosan MB, Oyekunle JAO: **Dietary exposure assessment of organochlorine pesticides in two commonly grown leafy vegetables in South-western Nigeria.** *Heliyon* 2019, **5**(6):e01895.
62. Akomea-Frempong S, Ofosu IW, Owusu-Ansah Ed-GJ, Darko G: **Health risks due to consumption of pesticides in ready-to-eat vegetables (salads) in Kumasi, Ghana.** *International Journal of Food Contamination* 2017, **4**(1):13.
63. Fothergill A, Abdelghani AJWToE, Environment t: **A review of pesticide residue levels and their related health exposure risks.** 2013, **170**:195-205.
64. Salazar JDJOoPM: **The OECD MRL Calculator.** 2011, **22**(2):77-79.
65. Odewale GO, Sosan MB, Oyekunle JAO, Adeleye AO: **Human health risk assessment of dichlorodiphenyltrichloroethane (DDT) and hexachlorocyclohexane (HCH) pesticide residues in fruits and vegetables in Nigeria.** *Environmental science and pollution research international* 2021.
66. Picó Y, El-Sheikh MA, Alfarhan AH, Barceló D: **Target vs non-target analysis to determine pesticide residues in fruits from Saudi Arabia and influence in potential risk associated with exposure.** *Food and chemical toxicology : an international journal published for the British Industrial Biological Research Association* 2018, **111**:53-63.
67. Szpyrka E: **Assessment of consumer exposure related to improper use of pesticides in the region of southeastern Poland.** *Environ Monit Assess* 2015, **187**(1):4140.
68. Park DW, Yang YS, Lee YU, Han SJ, Kim HJ, Kim SH, Kim JP, Cho SJ, Lee D, Song N *et al*: **Pesticide Residues and Risk Assessment from Monitoring Programs in the Largest Production Area of Leafy Vegetables in South Korea: A 15-Year Study.** *Foods* 2021, **10**(2).
69. Zhang Y, Si W, Chen L, Shen G, Bai B, Zhou C: **Determination and dietary risk assessment of 284 pesticide residues in local fruit cultivars in Shanghai, China.** *Sci Rep* 2021, **11**(1):9681.
70. Yi YJ, Joung HJ, Kum JY, Hwang IS, Kim MS: **Pesticide residues in vegetables and risk assessment for consumers in Korea during 2010-2014.** *Food additives & contaminants Part A, Chemistry, analysis, control, exposure & risk assessment* 2020, **37**(8):1300-1313.
71. Jacxsens L, Stals A, De Keuckelaere A, Deliens B, Rajkovic A, Uyttendaele M: **Quantitative farm-to-fork human norovirus exposure assessment of individually quick frozen raspberries and raspberry puree.** *International journal of food microbiology* 2017, **242**:87-97.
72. Adeleye AO, Sosan MB, Oyekunle JAO: **Occurrence and Human Health Risk of Dichlorodiphenyltrichloroethane (DDT) and Hexachlorocyclohexane (HCH) Pesticide Residues in Commonly Consumed Vegetables in Southwestern Nigeria.** *J Health Pollut* 2019, **9**(23):190909.
73. Szpyrka E, Kurdziel A, Matyaszek A, Podbielska M, Rupar J, Słowik-Borowiec M: **Evaluation of pesticide residues in fruits and vegetables from the region of south-eastern Poland.** *Food Control* 2015, **48**:137-142.
74. U.S. Environmental Protection Agency: **Guidance on Cumulative Risk Assessment of Pesticide Chemicals That Have a Common Mechanism of Toxicity.** In. Washington: Office of Pesticide Programs U.S. Environmental Protection Agency 2002: 90.

Figures

Figure 1

Hazard quotients for various pesticide residuals, for fruits and vegetables by stage of consumption along the chain

Figure 2

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