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Source: Environmental Health Insights, 16(1)

Published By: SAGE Publishing

URL: https://doi.org/10.1177/11786302221111866

Pesticide Residues in Fresh Fruit and Vegetables from Farm to Fork in the Kampala Metropolitan Area, Uganda

Environmental Health Insights
Volume 16: 1–17

DOI: 10.1177/11786302221111866

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ABSTRACT: This study assessed concentrations of pesticide residues in fruits and vegetables from farm-to-fork in Kampala Metropolitan Area, Uganda. A total of 160 samples of fruit and vegetables collected from farms, markets, streets, restaurants and homes were analysed using liquid chromatography–tandem mass spectrometry; and Gas Chromatograph–Mass Spectrometer for dithiocarbamates. Multiple pesticide residues were detected in majority of the samples (95.6%). The proportions of the most frequently detected pesticides residue classes were organophosphates (91.3%), carbamates (67.5%), pyrethroids (60.0%) dithiocarbamates (48.1%) and neonicotinoids (42.5%). Among organophosphates, propotamophos, acephate, fonofos, monocrotophos and dichlorvos were the most detected active ingredients; aminocarb, methomyl and pirimicarb were the commonly detected carbamates; while imidacloprid, a neonicotinoid and lambda-cyhalothrin, pyrethroid were also highly detected. Twenty-seven pesticide were tested at all stages, of which the concentrations either decreased or increased along the chain. Multiple pesticide residues occurred in commonly consumed fruit and vegetables with decreasing or increasing concentrations from farm-to-fork.

KEYWORDS: Fruit and vegetable production, farm to fork, samples, farmers, pesticides active ingredients, Uganda

RECEIVED: March 2, 2022. **ACCEPTED:** June 17, 2022.

TYPE: Original Research

FUNDING: The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research (or [initials]) was supported by the Consortium for Advanced Research Training in Africa (CARTA). CARTA is jointly led by the African Population and Health Research Centre and the University of the Witwatersrand and funded by the Carnegie Corporation of New York (Grant No—G-19-57145), Sida (Grant No:54100113), Uppsala Monitoring Centre and the DELTAS Africa Initiative (Grant No: 107768/Z/15/Z). The DELTAS Africa Initiative is an independent funding scheme of the African Academy of Sciences (AAS)'s Alliance for Accelerating Excellence in Science in Africa (AESA) and supported by the New Partnership for Africa's Development Planning and Coordinating Agency (NEPAD Agency) with funding from the Wellcome Trust (UK) and the UK government. The statements made and views expressed are solely the responsibility of the Authors. Research reported in this publication was partially support by the Fogarty International Center of the National Institutes of Health under Award Number D43TW009340. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

DECLARATION OF CONFLICTING INTERESTS: The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Introduction

Pesticides are substances used to control pests in agriculture, forestry, horticulture and on public lands to increase crop yields, improve the appearance of plant products, facilitate the care of open spaces and for public health purposes.[1] The use of pesticides has been increasing worldwide.[2] Global pesticide use is estimated at 6 million tonnes of active ingredients annually.[3] Forty seven percent of all pesticides are used in Europe, 24% in Asia, 23% in the United States of America (USA) and 5.8% in the rest of the world.[3] Herbicides, insecticides and fungicides are the most commonly used pesticides worldwide. Insecticides are more common in low-and middle-income countries (LMICs), whereas herbicides and fungicides are more heavily used in high income countries (HICs).[4] While Africa contributes 2% to 4% of the global pesticide consumption, their use has increased by 261% in recent years.[5] Approximately, Africa uses 1.8 million tonnes of pesticides, of which 153,901.4 tonnes are used annually in East Africa, where Uganda is located.[3]

Pesticide use for food production such as fruit and vegetable has improved food quantity and quality, consequently improving nutrition and international trade.[6,7] As such, pesticides are considered a necessary tool in the intensification of agriculture in order to meet the world's food demands.[8–10] Despite these benefits, excessive use of pesticides on fruits and vegetables to protect them from damage and loss by pests increases pesticide residues in these foods,[11] possibly reaching levels that are toxic to human health, especially if applied without following Good Agricultural Practices (GAPs).[12,13] Pesticide residues should not pose health risks if they are below the threshold of exposure known as Maximum Residue Limits (MRL). MRLs is the maximum amount of a pesticide residue allowed in food or animal feeds, expressed as milligrammes per kilogramme of the food.[14] The presence of pesticide residues in fruits and vegetables can potentially be toxic to human health if present in quantities above the MRL.[15]

Uganda is largely an agricultural-based economy, with this sector contributing more than 24.5% of the GDP and 75% of export earnings.[16] Horticulture, especially floriculture, is the fastest growing sub-sector but pests and diseases pose great challenges to farmers.[17] In order to reduce losses from fungal

and bacteria diseases, farmers often use pesticides on a daily basis and may not adhere to product label requirements.[18] Uganda uses 18,928.16 tonnes of pesticide every year, which is approximately 0.1% of global pesticide consumption.[3] However, this is almost 200 times more than the amount of pesticides used for food production in the 1960s.[3] Common pesticides used in Uganda include: fungicides (eg, mancozeb, tebuconazole and propineb); insecticides (eg, cypermethrin, dimethoate, dichlorvos and malathion); and herbicides (eg, glyphosate and 2,4-D-Amine).[19] In fact, these pesticides are ranked as hazardous to human health and the environment based on the FAO/WHO Joint Meeting on Pesticide Management Guidelines on Highly Hazardous Pesticides.[20] Majority of the pesticides used in Uganda are organophosphates, carbamates, pyrethroids and neonicotinoids.[21] Organophosphates and carbamates are highly soluble in water and volatile on exposure to sunlight,[22] but are known cholinesterase inhibitors that can impact neurodevelopment in humans.[23,24] Pyrethroids and neonicotinoids have high affinity to the soils with potential to bioaccumulate in the environment, but in humans are neurotoxins associated with poor development and neurological disorders.[25-27]

Quantifying pesticide residues in Ugandan foods can improve understanding of human exposure to pesticides in Uganda, providing evidence to inform policies intended to protect Uganda's community while at the same time supporting healthy food production practices. The very few studies that have examined pesticide residues in Ugandan produce have focussed on dithiocarbamate (Mancozeb) and organochlorines in tomatoes and carrots and reported levels that were above the Codex Alimentarius MRLs.[28-30] Whereas high income economies in the USA and European regions have programmes to monitor pesticide residues in foods,[31-33] because of limited resources low income countries like Uganda do not have similar programmes in place; yet, identifying and determining concentrations of trace pesticide contaminants in fruits and vegetables is critical to protect and improve human health while supporting a robust agricultural industry. In addition, several post-harvest handling techniques are practiced from the farm to the fork but these are not well documented. The farm to fork model looks at all stages of the supply chain including distribution, storage and handling from primary production to consumption.[34] It demonstrates that providing safe food to consumers is the responsibility of all stakeholders involved with production, processing, trade, cooking and serving.[34] In this paper, we measured pesticide residues concentrations in fruits and vegetables from farm to fork in Kampala Metropolitan Area (KMA).

Materials and Methods

Study area

We conducted the study in Kampala, Wakiso and Mukono Districts, 3 of the 5 districts that make up the KMA in Uganda. The 3 districts comprise 57 counties (262 sub-Counties and 1537 parishes) with a population of 10 812 700 people[35] and cover an area of 1000 km^2.[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 and restaurants and fruit and vegetable vending along the streets as well as many of the farms where fruits and vegetables consumed within central Uganda are grown. We sampled fruits and vegetables from smallholder farms, community markets, restaurants, street vendors and homes in the districts of Kampala, Wakiso and Mukono in KMA. Kampala, Wakiso and Mukono are inhabited by 15% of Uganda's population and contain Uganda's industrious districts that consume a big volume of the fruit and vegetables produced.

Produce sample collection

One hundred and sixty (160) samples of fruits and vegetables were collected from key stages along the chain that is farm (50), market (50), Street (20), restaurants (20) and homes (20). The 160 samples were equally distributed by fruits and vegetable type that is 32 each. At each stage along the chain, we collected equal numbers of fruit or vegetable samples.

A total of 50 farms were selected from Wakiso and Mukono with the help of agricultural extension workers and community leaders. From the farm, 10 community markets were identified to participate in the study based on their sales information. Street vendors, restaurants and homes were selected within communities served by selected markets with the help of community leaders. Fresh produce samples were collected in sterile polythene bags or PET (polyethylene terephthalate) plastic containers. During sampling, fruit and vegetables were purchased from farms, markets, restaurants, street vendors and homes. Each sample was assigned a unique identification number. Ready-to-eat food samples including juices and salads that do not contain fat-soluble substances were bought from restaurants. Restaurants were defined as facilities that prepare and serve food to customers during their hours of operation.[37] At homes identified through community leaders, household heads were asked to prepare samples of fruits and vegetables including juice, salad or sauce. Participating homes were compensated based on their estimation of the cost incurred to prepare the sample. Three replicate produce samples were collected at each location measuring at least 1 kg for small or medium fruits and/or vegetables and 2 kg for larger produce as suggested by Codex guidelines[38,39]; prepared food samples were at least 1 kg or 1 l in case of juice. The samples were stored in a cooler and transported to the Directorate of Government Analytical Laboratory (DGAL) within 8 hours. At DGAL, the samples were stored in the freezer at −20°C until preparation, extraction and analysis. At all stages along the chain, consent was sought from the person responsible prior to sample collection.

Chemicals and reagents used

Pesticide reference standards with purities between ⩾95% were purchased from Carlo Erba reagents (Val de Reuil, France). Reagents including methanol, water, ethyl acetate, cyclohexane, acetone, acetic acid 99%, ammonia formate, ammonia 25% NH3 (ca. 13.4 M), formic acid, sodium sulphate, water free. p.a., sodium hydrogen carbonate, water free. p.a., PSA 40 µm, toulene, acetonitrile, anhydrous magnesium sulphate and sodium chloride were sourced from Merck KGaA (Darmstadt, German) and VWR Prolabo Chemicals (BDH). The standard reagents and other analytical materials for dithiocarbamate (purity 74.0%) were obtained from Dr. Ehrenstorfer GmbH (Ausburg, Germany). The hydrochloric acid and stannous chloride were obtained from Sigma-Aldrich (St. Louis, USA); iso-octane was purchased from Fisher Scientific UK Ltd (Loughborough, England); and lactose was obtained from LabChemie (Mumbai, India).

Sample preparation and extraction

A total of 93 pesticides residues were screened in the produce and prepared samples. The samples were prepared, cleaned and extracted using the modified Quick, Easy, Cheap, Effective, Rugged and Safe (QuEChERS acetate) approach for determination of pesticide residues.[40,41] Briefly, 1 to 2 kgs of each sample was chopped, grinded and blended to homogenise the sample; homogenisation was conducted for 0.5 to 1 minute to avoid enzymatic degradation of the analytes. After homogenisation, 200 g of the sample were picked and put into containers and immediately frozen in order to minimise the risk for degradation of pesticide residues present. Ten grams of homogenised sample was weighed into a 50 ml polypropylene centrifuge tube containing 3*g* of sodium bicarbonate ($NaHCO_3$), added 10.0 ml ethyl acetate and vortexed for 1 minute, added 10 g anhydrous sodium sulphate and homogenised it at 15 000 rpm for 2 minutes. The mixture was centrifuged at 5000 rpm for 5 minutes. For LC-MS/MS amenable compounds, 5 ml supernatant was placed into a 15 ml polypropylene tube containing 25 mg of primary secondary amine (PSA), which was then shaken for 30 seconds before centrifuging it for 5 minutes at 10 000 rpm. 2 ml supernatant was drawn into a test tube containing 200 µl of 10% diethylene glycol (DEG) solution, then evaporated it to dryness under nitrogen at 350°C. The residue was reconstituted with 0.9 ml of methanol and 0.1 ml of 0.1% acetic acid in the water, sonicated for 1 minute and vortexed for 30 seconds. The reconstituted extract was centrifuged at 10 000 rpm for 5 minutes and filtered through a 0.2 µm Nylon 6,6 membrane filtre into an LC vial. Injected 10 µl from the extract into the LC-MS/MS. For GC-MS/MS analysis, 1 ml supernatant in the Eppendorf tube containing 25 mg PSA was taken and shaken vigorously for 30 seconds. it was then centrifuged at 10 000 rpm for 5 minutes before picking off 0.5 ml clear supernatant extract in a GC auto sampler vial. The cleaned extract was injected into the GC-MS/MS for pesticide residue analysis.

Solutions and standards used

Individual standards were prepared gravimetrically in ~1000 mg/l concentration by weighing 10 mg from each standard mix into a 20 mL amber screw cap vial on a 5-digit analytical balance and dissolving in 10 mL of appropriate solvent (acetone, toluene or acetonitrile depending its compatibility with the LC or GC-MS/MS). Concentrations of each individual standard mix stock solution was calculated gravimetrically using weight of added compounds and solvents. All individual standard stocks were stored in a freezer at −20°C. Validity of individual standard mix stock solutions was 6 months. Working solutions were prepared by serial dilution.

Quality control

To ensure quality control of results during the study, different measures were employed from the sampling stage, through sample homogenisation, extraction, sample analysis on machine up to data interpretation. The different measures included use of a validated sampling protocol which guided on how representative samples from field were to be picked, on how systematic labelling had to be done and the same protocol guided on how the sampled samples were to be transported from field to the laboratory under cold chain in a cool box to minimise cross-contamination of samples.

During sample extraction, quality control was enforced through inclusion of reagent blanks, same sample matrix blanks and quality control samples acquired from Fera Science Ltd (FAPAS) to monitor any possible errors during analysis as well as monitoring the method batch recovery for the analytes in the quality control sample as a representation of the analytes under monitoring.

External quality control of the laboratory was assessed through FAPAS proficiency testing Scheme which the laboratory participates in annually with the most recent participation in the scheme being FAPAS, 2021. Food Analysis Performance Assessment Scheme. Food Chemistry Proficiency Test report 19311, May-June 2021. The Food and Environment Research Agency (Fera) Science Ltd, York Biotech Campus, Sand Hutton, York Y041 1LZ UK. where the allocated laboratory number is 14., with its participation in the PT yielding satisfactory results for the analytes tested.

Quality control during data interpretation was based on the method validation data where method performance parameters like; Lowest limit of detection (LOD), Lowest limit of Quantification (LOQ), Matrix effect and Recovery had been assessed before employment of the method in analysis. All samples were analysed in triplicates and standard deviation of results had to be within the acceptable limits before sample results were validated and these where based on SANTE/12682/2019

Liquid chromatography – Tandem mass spectrometry analysis

Pesticide residue analysis was carried using an Agilent Liquid Chromatography – Tandem Mass Spectrometer (LC-MS/MS) (Agilent Technologies, Santa Clara, California, USA) system as described in Ssemugabo, Guwatudde, Ssempebwa, Bradman.[42] Briefly, chromatographic separation of the targetted analytes was performed using ZORBAX RRHD Eclipse plus C18 Capillary column with dimensions, 2.1 ×150 mm, 1.8 µm (part number 959759-902) installed on an Agilent 1290 Infinity II LC system having Agilent 1290 Infinity II high-speed pump (G4220A), Agilent 1290 Infinity II autosampler (G4226A) and Agilent 1290 Infinity II thermostatted column Compartment (G1316C). The LC conditions used were as follows; - Column temperature was set at 40°C, injection volume was 5 µl, mobile phase A was 5 mM ammonium formate in water with 0.1% formic acid and mobile phase B was 5 mM ammonium formate in Methanol with 0.1% formic acid. The mobile phase flow rate was 0.3 µl/min. The gradient elution programme was 5% B at 0 minute, 30% B at 3 minutes, 100% B at 17 minutes, 100% B at 20 minutes and postrun 3 minutes.

Analysis for dithiocarbamates

The method used to determine dithiocarbamates (mancozeb, maneb, dithane, thiram, metam sodium and propineb) was developed Keppel at the United States Food and Drug Administration (U.S. FDA).[43,44]

Frozen sub-sample of 10 g were placed into a Duran bottle (250 ml) and mixed with isooctane (20 ml) followed by stannous chloride (reducing solution) in hydrochloric acid (100 ml), 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 place in a vial prior to the quantitation of carbon disulphide by Gas Chromatography-Mass spectrometry (GC–MS). Procedural recoveries were determined concurrently with each batch of analytical extracts by analysing the carbon disulphide that evolved after digestion of the spiked fruit or vegetable samples with dithiocarbamate standard. The spiking was done twice, once at the level of limit of quantitation (LOQ) (50 µg/kg) and the other at expected residue level (1000 µg/kg). These values were obtained from previous runs during instrument optimisation. Analysis was done from calibrations using dithiocarbamate Certified Reference Standard, corrected for purity and prepared in lactose. A 5-point calibration was done, ranging from 0.125 to 5 µg/ml. The method's LOQ was set at 0.05 mg/kg which equates to the calibration standard of 0.125 µg/ml. All extracts were analysed using GC-MS (Shimadzu QP2010, Kyoto, Japan). The column used was an Agilent (Santa Clara, USA) J&W GC column (GS-GASPRO, length 30 m, diameter 0.32 mm with no film thickness). The system was calibrated daily using perfluorotributylamine. In addition, system blanks and known standards were run to monitor performance and sensitivity. The GC initial temperature was 60°C held for 2.5 minutes and then increased to 260°C at a rate of 15°C/min. The total run time was 15.83 minutes. Sample volumes of 1.0 µl were injected in a spitless mode with a solvent cut of 3 minutes. Initially, a standard at a high concentration was run in full scan acquisition mode, the MS was in positive electron impact mode at 70 eV and mass detection range was a mass-to-charge ratio (mz) of 40 to 550. Ion source was set at 200°C and interface temperature was 260°C. The peaks were confirmed with NIST/EPA Mass Spectral library. The carrier gas was helium (purity 99.999%) at flow rate of 2.0 ml/min. From this, a selected ion monitoring (SIM) method was developed with the target ion for carbon disulphide being mz 76 along with 44 and 78 as reference ions.

Statistical analysis

Data were analysed using Stata version 15 (Statacorp Texas; USA). Pesticide residues concentrations were expressed in µg/kg. We first summarised descriptive statistics for all analytes detected, and then by point in the supply chain and fruit and vegetables type. Only pesticides with concentration above the limit of detection (LOD) were presented.

Ethical considerations

Ethical approval for 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 (owners of farms, and restaurants, market managers, street fruit and vegetable vendors and household heads) provided written consent to collect samples. All samples were coded with an anonymous identification number.

Results

Classes of pesticides residues detected in the fruits and vegetables samples

Twenty-one pesticide classes were detected in the fruit and vegetable samples (Table 1). The most frequent pesticide residue detected were organophosphate, carbamates, pyrethroids, dithiocarbamates, neonicotinoids, chloroacemide and pnilinopyrimidine, pesticides found in 91.3%, 67.5%, 60.0%, 48.1%, 25% and 23.8% of the samples, respectively. All samples had at least one detected analyte.

Table 1. Classes of pesticide residues detected in fruits and vegetables samples collected from farm to fork.

CHEMICAL FAMILY OF PESTICIDE	FREQUENCY (N = 160)	PERCENTAGE (%)
Organophosphates	146	91.3
Carbamates	108	67.5
Pyrethroids	96	60.0
Dithiocarbamates	77	48.1
Neonicotinoids	68	42.5
Chloroacetamide	40	25.0
Anilinopyrimidine	38	23.8
Pyrimidine	35	21.9
Imidazole	34	21.3
Tetramic acid	20	12.5
Benzoylurea	17	10.6
Benzimidazole	16	10.0
Triazole	15	9.4
Hydroxyanilide	11	6.9
Quinoline	10	6.3
Quinazolinone	6	3.8
Strobilurin	5	3.1
Aryloxyphenoxypropionate	4	2.5
Phenylamide	2	1.3
Isoxazolidinone	1	0.6
Others (unclassified)	1	0.6

Occurrence of multiple pesticides residues in fruits and vegetable samples

Multiple pesticide residues (up to 19 in 1 sample) were detected in many samples. For example, 41 samples (25.6%) had >10 active ingredients detected and 102 samples (63.8%) had 2 to 9 active ingredients (Table 2).

Concentration of pesticide residues detected

Table 4 shows the distribution of pesticide analytes detected. Overall, 58 out of the 93 analytes measured were detected in at least one sample (Table 3). Of the 58, 24 were organophosphate (OPs), 10 carbamates, 3 neonicotinoids, 4 pyrethroid and 16 were from other classes such as triazole, chloroacetamide and phenylamide among others. Dithiocarbamates were detected in 48% of the samples. Common organophosphates detected were acephate (32.5%), propetamophos (48.5%), fenofos (28.8%), monocrotophos (21.9%) and dichlorvos (18.8%). Commonly detected carbamates included aminocarb (20.6%), methomyl (21.3%) and pirimicarb (19.4%). Common neonicinotoids detected included imidacloprid (30.0%) and acetamiprid (18.8%). Commonly detected pyrethroids included lambda-cyhalothrin (40.0%), cypermethrin (20.6%) and bifenthrin (19.4%). Among other pesticides classes, metazaclor, pyrimethanil, fenarimol and imazalil were frequently detected (25.0%), (23.8%), (21.9%) and (21.3%) respectively.

Concentration of pesticide residues from farm to fork

Twenty-seven pesticide residues were detected at all levels sampled along the supply chain. Concentrations for 18 pesticides including dithiocarbamates, acephate, mevinphos, azamethiphos, dichlorvos, profenofos, aminocarb, methomyl, methiocarb, dioxacarb, benfuracarb, bifenthrin, acetamiprid, lambda-cyhalothrin, cypermethrin, spiritetramat, flufenoxuron and proquinazid were detected at all levels and their concentration decreased along the supply chain from farm to fork (see Supplemental Figures 1–18). Nine pesticide active ingredients that is fonofos, methidathion, isofenphosmethyl, ethoprophos, quinalphos, carbaryl, azoxystrobin, fenhexamid and fenarimol (see Supplemental Figures 19–27), were also detected through the chain but their concentration increased from farm to fork (Table 4).

Pesticide residue concentration by fruits and vegetables types

Overall, detected pesticide residue concentrations and detection frequencies were equally distributed in fruits and vegetables. While most of the 58 detected pesticide residue were found in both fruits and vegetables, only Malathion, Deltamethrin, Azoxystrobin and Clomazone were not found in the fruit samples tested (water melon and passion fruits) (Table 5).

Discussion

In this study, we measured pesticide concentrations in selected fruit and vegetables along the supply chain from farm to fork. Organophosphate, carbamate, pyrethroid, dithiocarbamate and neonicotinoid pesticides were commonly detected in these foods. Almost all pesticides were detected in fruit and vegetables accept malathion, deltamethrin, azoxystrobin and alomazone that were not detected in fruits. The majority of the samples had multiple pesticide residues detected in them. Along the supply chain, concentrations of 18 pesticides decreased while 9 increased.

A total of 58 pesticides residues were detected from the 160 fruit and vegetable samples collected. Our findings present higher number of pesticide residues detected than reports from other studies in Africa.[45-49] For example, studies in Tanzania,

Table 2. Number of pesticide residues detected in per fruit and vegetable samples.

NUMBER OF PESTICIDE RESIDUES DETECTED	FARM (N=50)	MARKET (N=50)	RESTAURANT (N=20)	STREET (N=20)	HOME (N=20)	TOTAL (N=160)
	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)
1	0 (0.0)	1 (2.0)	1 (5.0)	1 (5.0)	4 (20.0)	7 (4.4)
2	2 (4.0)	4 (8.0)	2 (10.0)	2 (10.0)	1 (5.0)	11 (6.9)
3	4 (8.0)	4 (8.0)	2 (10.0)	1 (5.0)	1 (5.0)	12 (7.5)
4	9 (18.0)	1 (2.0)	2 (10.0)	3 (15.0)	3 (15.0)	18 (11.3)
5	3 (6.0)	12 (14.0)	2 (10.0)	1 (5.0)	0 (0.0)	18 (11.3)
6	2 (4.0)	4 (8.0)	1 (5.0)	3 (15.0)	0 (0.0)	10 (6.3)
7	4 (8.0)	3 (6.0)	0 (0.0)	0 (0.0)	1 (5.0)	8 (5.0)
8	10 (20.0)	3 (6.0)	0 (0.0)	4 (20.0)	1 (5.0)	18 (11.3)
9	3 (6.0)	1 (2.0)	1 (5.0)	1 (5.0)	1 (5.0)	7 (4.4)
10	5 (10.0)	1 (2.0)	1 (5.0)	0 (0.0)	3 (15.0)	10 (6.3)
11	3 (6.0)	6 (12.0)	1 (5.0)	1 (5.0)	0 (0.0)	11 (6.9)
12	1 (2.0)	1 (2.0)	4 (20.0)	0 (0.0)	0 (0.0)	6 (3.8)
13	1 (2.0)	4 (8.0)	0 (0.0)	0 (0.0)	2 (10.0)	7 (4.4)
14	2 (4.0)	3 (6.0)	0 (0.0)	2 (10.0)	1 (5.0)	8 (5.0)
15	1 (2.0)	2 (4.0)	0 (0.0)	0 (0.0)	2 (10.))	5 (3.1)
16	0 (0.0)	0 (0.0)	2 (10.0)	0 (0.0)	0 (0.0)	2 (1.3)
19	0 (0.0)	0 (0.0)	1 (5.0)	1 (5.0)	0 (0.0)	2 (1.3)
Total	50 (100)	50 (100)	20 (100)	20 (100)	20 (100)	160 (100)

Table 3. Limits of detection and summary statistics for pesticide residues concentrations in fruits and vegetables samples collected from farm to fork (n=160).

PESTICIDE	LOD (µG/KG)	DF	MIN	P25	P50	P75	P95	MAX
Dithiocarbamates[a]	0.006	77	–	–	–	0.5	2.1	3.9
Organophosphates								
Omethoate	0.01	12	–	–	–	–	0.2	12.4
Acephate	0.03	52	–	–	–	0.2	2.5	17.8
Monocrotophos	0.01	35	–	–	–	–	0.6	0.5
Vamidothion	0.01	18	–	–	–	–	0.09	0.7
Dimethoate	0.008	1	–	–	–	–	–	23.2
Mevinphos	0.03	21	–	–	–	–	0.08	0.8
Phosphamidon	0.02	11	–	–	–	–	0.02	0.3
Fonofos	0.01	46	–	–	–	4.4	920.9	2590.7
Azamethiphos	0.005	13	–	–	–	–	0.03	0.5
Dichlorvos	0.02	30	–	–	–	–	4.0	115.2
Malaoxon	0.01	15	–	–	–	–	0.04	1.1

(Continued)

Table 3. (Continued)

PESTICIDE	LOD (μG/KG)	DF	MIN	P25	P50	P75	P95	MAX
Methidathion	0.01	3	–	–	–	–	–	0.4
Malathion	0.02	3	–	–	–	–	–	2.3
Methacrifos	0.005	2	–	–	–	–	–	1.0
Propetamophos	0.008	76	–	3.7	21.8	30.3	34.5	43.2
Isofenphosmethyl	0.02	14	–	–	–	–	2.4	4.6
Ethoprophos	0.08	3	–	–	–	–	–	0.4
Fenamiphos	0.009	10	–	–	–	–	0.02	0.05
Quinalphos	0.03	16	–	–	–	–	0.5	1.6
Chlorpyriphos-methyl	0.008	8	–	–	–	–	0.04	2.7
Temephos	0.008	4	–	–	–	–	–	0.2
Profenofos	0.01	22	–	–	–	–	38.4	406.4
Pirimiphosmethyl	0.02	1	–	–	–	–	–	206.6
Fenitrothion	0.01	28	–	–	–	–	113.8	505.6
Carbamates								
Aminocarb	0.02	33	–	–	–	–	0.1	22.4
Methomyl	0.03	34	–	–	–	–	0.3	0.5
Aldicarbfragment	0.01	18	–	–	–	–	0.2	0.5
Pirimicarb	0.03	31	–	–	–	–	0.08	0.7
Dioxacarb	0.01	12	–	–	–	–	24.8	104.5
Carbaryl	0.008	9	–	–	–	–	0.009	0.2
Carbofuran	0.009	8	–	–	–	–	–	0.9
Alanycarb	0.01	26	–	–	–	1.2	108.4	209.4
Benfuracarb	0.05	12	–	–	–	–	40.1	878.5
Methiocarb	0.04	19	–	–	–	–	0.1	0.3
Neonicotionides								
Imidacloprid	0.03	48	–	–	–	0.3	2.6	8.1
Acetamiprid	0.02	30	–	–	–	–	18.7	126.6
Thiacloprid	0.01	3	–	–	–	–	–	0.2
Pyrethriods								
Bifenthrin	0.02	31	–	–	–	–	0.5	6.8
Lambda-Cyhalothrin	0.02	64	–	–	–	0.2	0.9	2.5
Deltamethrin	0.01	3	–	–	–	–	–	1786.7
Cypermethrin	0.01	33	–	–	–	–	1.7	15.6
Others								
Carbendazim	0.02	16	–	–	–	–	–	4.2
Imazalil	0.01	34	–	–	–	–	2.0	7.6
Metazachlor	0.01	40	–	–	–	–	0.1	1.0

(Continued)

Table 3. (Continued)

PESTICIDE	LOD (μG/KG)	DF	MIN	P25	P50	P75	P95	MAX
Metalaxyl	0.02	2	–	–	–	–	–	1.4
Azaconazole	0.006	14	–	–	–	–	0.3	1.6
Clomazone	0.007	1	–	–	–	–	–	0.05
Azoxystrobin	0.007	5	–	–	–	–	12.4	66.5
Pyrimethanil	0.02	38	–	–	–	0.2	0.4	0.7
Spirotetramat	0.02	20	–	–	–	–	0.1	1.0
Fenhexamid	0.01	11	–	–	–	–	156.5	493.7
Fenarimol	0.01	35	–	–	–	–	3.0	10.4
Fluazifop	0.02	4	–	–	–	–	–	171.0
Flufenoxuron	0.02	17	–	–	–	–	0.02	0.2
Pyriproxyfen	0.007	1	–	–	–	–	–	0.05
Quinoxyfen	0.03	10	–	–	–	–	0.2	0.5
Proquinazid	0.01	6	–	–	–	–	2.4	8.0

Abbreviations: DF, detection frequency; LOD, limit of detection; Max, maximum concentration; ND, not detected; p25, 25th percentile; p50, median (50th percentile); p75, 75th percentile; p95, 95th percentile.
[a]Mancozeb, Maneb, Metiran, Pronineb, Thiram and Zinam expressed in CS_2.

Kenya and Algeria found 7 or less active ingredients in produce samples.[45,46,48] Occurrence of multiple pesticides residues could be as a result of plant uptake of persistent pesticides[50] and spray drift.[51,52] Multiple pesticide residues might also be as a result of poor agricultural practices especially the use of cocktail of pesticides. Indeed, the use of cocktails of pesticides has been observed among Uganda farmers[17,53,54] and among others farmers in Africa.

Fruit and vegetable farmers are faced with many insects that infest and reduce the quality of their produce. This largely explains why insecticides especially organophosphates and carbamates were the most commonly detected pesticides. Similar studies carried out in Ghana, Malawi, Tanzania, Botswana, Algeria and Uganda indicate that organophosphates, carbamates, dithiocarbamates, pyrethroids and neonicotinoids, all insecticides, are the most common pesticide residues detected in fruits and vegetables in Africa.[30,45-49,55,56]

Two or more – up to 19 pesticide active ingredients were detected in 95.6% of the fruit and vegetable samples, indicating their mixed use on the farm. Although in relatively lower percentages, studies from Botswana, Algeria and Kuwait revealed 33.4%, 47% and 40% fruit and vegetable samples with multiple pesticides residues,[48,57,58] findings that collaborate with those from our study. Due to pest resistance, farmers are applying multiple pesticides on fruits and vegetables.[59] In addition, recent studies suggest that farmers may use pesticide in ways that are not compliant with label requirements,[60] leading to pesticide resistance and thus the need to use multiple pesticides. This presents a risk of exposure to a mixture of pesticides to farmers as well as the consumers.

Almost all pesticide found in fruits and vegetables were registered for use in Uganda.[61] However, monocrotophos found in some samples is banned in Uganda.[61] Monocrotophos is ranked as a highly hazardous pesticide according to the WHO recommended classification of pesticides by hazards.[62] Monocrotophos use might be as a result of illegal importation or smuggling of pesticides across borders by farmers or traders. Methidathion and thiacloprid banned in the European union and the United States of America were also detected. Although, not banned in Uganda, their concentration levels in fruits and vegetables could affect the Uganda's exportation of fruits and vegetables to the EU and USA.

Twenty-seven pesticides were detected at all levels from farm to fork with 18 and 9 of the chemicals reducing and increasing respectively along the chain. The reduction in the concentration of pesticide residues along the supply chain might be as a result of handling and processing methods that the different stakeholders along the chain applied on the produce. Previous studies have shown that handing and processing methods like washing, peeling, soaking, boiling, blanching, steaming, canning scrambling and cooking[63-66] as well as freezing and juicing[67,68] reduce the concentration of pesticide residues in fruits and vegetables. Conversely, drying/dehydration and concentration have been shown to increase pesticide residues in fruits and vegetables.[65,67] In fact, processing methods like baking, boiling, canning and juicing have been found to increase concentration of pesticide per unit volume.[68,69] The increase of pesticide residues along the chain could also be explained by the fact that we took fruits and vegetables from different samples at different stages along the chain. In

Table 4. Pesticide residue concentration in fruit and vegetable samples by stage of sampling along the supply chain.

PESTICIDE	LOD (μG/KG)	FARM			MARKET			STREET			RESTAURANT			HOME		
		DF	P95	MAX	DF	P95	MAX	DF	P95	MAX	DF	P95	MAX	DF	P95	MAX
Dithiocarbamate[a]	0.006	22	2.5	3.2	29	1.6	2.8	11	3.0	3.6	7	2.8	3.9	8	1.3	1.4
Organophosphate																
Omethoate	0.01	2	–	0.3	3	2.0	12.4	ND	–	–	5	3.7	6.0	2	0.05	0.1
Acephate	0.03	17	5.8	8.4	19	2.9	17.8	3	0.7	0.7	7	1.3	1.7	6	0.7	0.8
Monocrotophos	0.01	13	0.1	0.2	8	0.2	0.5	3	0.3	0.4	6	0.3	0.3	5	0.1	0.2
Vamidothion	0.01	6	0.08	0.7	13	0.3	0.4	5	0.01	0.02	4	0.05	0.06	2	0.05	0.1
Dimethoate	0.008	ND	–	–	1	–	23.2	ND	–	–	ND	–	–	ND	–	–
Mevinphos	0.03	9	0.3	0.6	6	0.1	0.8	2	0.04	0.06	3	0.03	0.05	1	0.1	0.3
Phosphamidon	0.02	2	–	0.07	5	0.04	0.3	2	0.2	0.3	ND	–	–	2	0.03	0.05
Fonofos	0.01	17	843.2	1013.9	17	993.7	2590.7	4	6.7	6.9	4	1092.9	1111.3	4	688.9	922.2
Azamethiphos	0.005	4	0.05	0.1	2	–	0.5	3	0.02	0.04	3	0.07	0.09	ND	–	–
Dichlorvos	0.02	11	57.9	115.2	6	0.9	1.9	4	0.4	0.6	4	2.4	4.3	5	3.5	4.0
Malaoxon	0.01	3	0.01	0.2	6	0.04	0.2	1	0.5	1.2	2	0.1	0.2	3	0.1	0.1
Methidathion	0.01	ND	–	–	ND	–	–	1	0.02	0.02	ND	–	–	2	0.4	0.4
Malathion	0.02	2	–	2.3	ND	–	–	ND	–	–	ND	–	–	1	0.05	0.1
Methacrifos	0.005	ND	–	–	2	–	1.0	ND	–	–	ND	–	–	ND	–	–
Propetamophos	0.008	23	33.6	33.7	13	37.2	43.2	1	36.3	36.3	4	25.9	25.9	2	23.6	23.6
Isofenphosmethyl	0.02	5	1.9	2.2	3	0.3	1.2	1	2.7	2.7	1	0.6	0.6	4	4.6	4.6
Ethoprophos	0.08	ND	–	–	1	–	0.4	ND	–	–	1	0.2	0.2	1	0.4	0.4
Fenamiphos	0.009	1	–	–	3	–	0.03	4	0.05	0.05	2	0.03	0.03	ND	–	–
Quinalphos	0.03	2	0.2	0.3	5	0.5	0.8	1	0.6	0.6	3	1.6	1.6	5	0.4	0.4
Chlorpyriphos-methyl	0.008	4	0.3	2.7	ND	–	–	1	0.05	0.09	3	1.0	1.5	ND	–	–
Temephos	0.008	ND	–	–	1	–	0.1	ND	–	–	2	0.05	0.05	1	0.2	0.2
Profenofos	0.01	5	159.1	406.4	8	20.9	261.7	3	55.5	85.7	4	86.5	119.7	2	7.2	11.2
Pirimiphosmethyl	0.02	ND	`	–	1	–	0.2	ND	–	–	ND	–	–	ND	–	–
Fenitrothion	0.01	9	65.0	495.1	6	79.3	180.7	5	327.0	505.6	6	228.6	289.1	2	43.4	63.1

(Continued)

Table 4. (Continued)

PESTICIDE	LOD (μG/KG)	FARM			MARKET			STREET			RESTAURANT			HOME		
		DF	P95	MAX	DF	P95	MAX	DF	P95	MAX	DF	P95	MAX	DF	P95	MAX
Carbamates																
Aminocarb	0.02	10	0.09	1.7	10	0.1	22.4	4	0.1	0.2	4	0.1	0.1	5	0.08	0.1
Methomyl	0.03	11	0.3	0.4	15	0.3	0.5	2	0.07	0.1	4	0.3	0.4	2	0.05	0.09
Aldicarbfragment	0.01	5	0.3	0.4	7	0.2	0.2	2	0.3	0.5	2	0.1	0.3	2	0.2	0.3
Pirimicarb	0.03	14	0.2	0.4	8	0.03	0.6	ND	–	–	5	0.5	0.7	4	0.08	0.08
Dioxacarb	0.01	7	39.9	104.5	7	45.3	79.5	1	34.6	69.2	ND	–	–	ND	–	–
Carbaryl	0.008	3	–	0.2	3	0.05	0.09	1	0.03	0.06	ND	–	–	2	0.2	0.2
Carbofuran	0.009	3	0.06	0.1	1	–	0.009	1	0.5	1.0	2	0.4	0.8	1	–	0.009
Alanycarb	0.01	6	100.9	153.4	8	102.7	209.4	3	68.7	68.7	3	114.1	114.1	6	146.2	146.2
Benfuracarb	0.05	4	48.7	878.5	3	52.7	142.7	3	15.6	15.6	1	–	–	1	31.5	31.5
Methiocarb	0.04	7	0.2	0.3	4	0.07	0.2	4	0.1	0.1	2	0.06	0.06	2	–	–
Neonicotinoids																
Imidacloprid	0.03	10	3.0	5.3	19	1.7	5.0	8	5.0	8.1	8	6.4	7.5	5	1.1	1.1
Acetamiprid	0.02	6	47.2	12.7	13	21.4	58.2	5	13.3	18.4	4	17.5	19.0	2	8.1	9.2
Thiacloprid	0.01	3	0.03	0.2	ND	–	–	ND	–	–	ND	–	–	ND	–	–
Pyrethroid																
Bifenthrin	0.02	11	0.8	2.5	13	1.4	6.8	1	0.08	0.2	4	0.2	0.3	2	0.04	0.05
Lambda-Cyhalothrin	0.02	19	0.9	1.8	19	0.9	2.5	7	1.0	1.0	10	0.7	0.9	9	0.7	0.9
Deltamethrin	0.01	2	–	0.2	1	–	1.8	ND	–	–	ND	–	–	ND	–	–
Cypermethrin	0.01	8	9.0	15.6	12	1.3	7.6	5	8.0	12.1	5	1.5	2.0	3	1.0	1.5

(Continued)

Table 4. (Continued)

PESTICIDE	LOD (μG/KG)	FARM			MARKET			STREET			RESTAURANT			HOME		
		DF	P95	MAX	DF	P95	MAX	DF	P95	MAX	DF	P95	MAX	DF	P95	MAX
Others																
Carbendazim	0.02	2	–	0.07	4	0.1	4.2	4	0.03	0.03	4	0.09	1.0	2	–	0.02
Imazalil	0.01	12	2.1	3.9	12	1.3	1.7	4	4.9	5.9	2	4.0	7.6	4	2.6	3.0
Metazachlor	0.01	11	0.1	0.8	12	0.1	1.0	7	0.2	0.2	5	0.2	0.3	5	0.1	0.1
Metalaxyl	0.02	1	–	0.1	1	–	1.4	ND	–	–	ND	–	–	ND	–	–
Azaconazole	0.006	2	0.01	0.2	6	0.4	1.6	4	0.3	0.3	ND	–	–	2	0.4	0.4
Clomazone	0.007	1	–	0.05	ND	–	–	ND	–	–	ND	–	–	ND	–	–
Azoxystrobin	0.007	2	33.0	50.9	ND	–	–	ND	–	–	2	18.4	18.4	1	66.5	66.5
Pyrimethanil	0.02	7	0.2	0.6	13	0.4	0.4	5	0.6	0.6	5	0.3	0.3	8	0.7	0.7
Spirotetramat	0.02	9	0.07	1.0	3	0.1	0.5	2	0.3	0.3	2	0.03	0.03	4	0.07	0.07
Fenhexamid	0.01	3	144.8	168.2	3	205.6	369.3	2	493.7	493.7	1	15.0	15.0	4	6.4	6.4
Fenarimol	0.01	12	2.0	6.0	9	0.4	4.1	5	2.0	2.6	5	3.4	3.4	4	7.1	10.4
Fluazifop	0.02	2	–	3.6	2	–	171.0	ND	–	–	ND	–	–	ND	–	–
Flufenoxuron	0.02	6	0.04	0.2	6	0.02	0.08	1	–	–	3	0.02	0.03	1	–	0.02
Pyriproxyfen	0.007	ND	–	–	ND	–	–	1	0.05	0.05	ND	–	–	ND	–	–
Quinoxyfen	0.03	5	0.2	0.5	1	–	0.3	1	0.5	0.5	2	0.02	0.02	1	0.5	0.5
Proquinazid	0.01	3	4.0	8.0	1	–	3.0	1	4.3	4.3	1	1.7	1.7	ND		

Abbreviations: DF, detection frequency; LOD, limit of detection; Max, maximum concentration; ND, not detected; p95, 95th percentile.
[a]Mancozeb, Maneb, Metiran, Pronineb, Thiram and Zinam expressed in CS_2.

Table 5. Pesticide residue concentration by fruits and vegetable type.

PESTICIDE	LOD (μG/KG)	WATER MELON			PASSION FRUIT			TOMATO			CABBAGE			EGG PLANT		
		DF	P95	MAX	DF	P95	MAX	DF	P95	MAX	DF	P95	MAX	DF	P95	MAX
Dithiocarbamate[a]	0.006	18	2.8	3.9	9	0.4	0.7	13	1.4	1.7	20	3.2	3.6	17	1.4	1.8
Organophosphates																
Omethoate	0.01	2	0.3	12.4	1	–	6.0	5	1.5	7.7	1		0.1	3	0.2	1.9
Acephate	0.03	12	4.0	1.8	12	7.4	8.4	10	0.8	0.8	11	1.4	1.7	7	0.7	0.9
Monocrotophos	0.01	7	0.2	0.3	10	0.3	0.4	5	0.1	0.1	11	0.1	0.2	2	0.1	0.5
Vamidothion	0.01	3	0.06	0.08	1	–	0.03	2	0.02	0.1	3	0.08	0.1	9	0.7	0.7
Dimethoate	0.008	1	–	23.2	ND	–	–	ND	–	–	ND	–	–	ND	–	–
Mevinphos	0.03	5	0.04	0.07	2	0.1	0.6	2	0.04	0.05	7	0.3	0.8	5	0.6	0.7
Phosphamidon	0.02	2	0.02	0.05	3	0.04	0.3	ND	–	–	2	–	–	4	0.07	0.3
Fonofos	0.01	7	64.9	771.5	9	1074.5	1111.3	9	1013.9	2590.7	9	919.5	1441.2	12	812.0	846.0
Azamethiphos	0.005	4	0.1	0.5	3	0.09	0.1	2	–	0.02	3	0.006	0.06	1	–	0.05
Dichlorvos	0.02	7	2.2	87.7	7	57.9	115.2	5	1.5	1.9	4	1.7	3.9	7	5.2	5.6
Malaoxon	0.01	4	0.05	0.09	1	–	0.01	2	0.08	1.1	6	0.2	0.2	2	0.02	0.2
Methidathion	0.01	ND	–	–	1	0.05	0.05	1	0.4	0.4	ND	–	–	1	0.02	0.02
Malathion	0.02	ND	–	–	ND	–	–	1	–	0.2	1	–	0.1	1	–	2.3
Methacrifos	0.005	ND	–	–	1	–	1.0	ND	–	–	1	–	0.07	ND	–	–
Propetamophos	0.008	16	43.2	43.2	15	33.6	33.6	15	34.8	34.8	14	34.1	34.1	16	32.7	32.7
Isofenphosmethyl	0.02	3	2.7	2.7	3	1.9	1.9	2	0.6	0.6	4	4.6	4.6	2	3.0	3.0
Ethoprophos	0.08	1	0.4	0.4	1	0.2	0.2	ND	–	–	ND	–	–	1	0.4	0.4
Fenamiphos	0.009	3	0.03	0.03	1	–	–	1	0.03	0.03	3	0.02	0.02	2	O.05	0.05
Quinalphos	0.03	6	0.6	0.6	4	0.8	0.8	3	0.3	0.3	1	0.1	0.1	2	1.6	1.6
Chlorpyriphos-methyl	0.008	2	0.008	0.09	2	0.3	0.9	2	0.1	2.7	1		1.5	1	-	0.6

(Continued)

Table 5. (Continued)

PESTICIDE	LOD (μG/KG)	WATER MELON			PASSION FRUIT			TOMATO			CABBAGE			EGG PLANT		
		DF	P95	MAX	DF	P95	MAX	DF	P95	MAX	DF	P95	MAX	DF	P95	MAX
Temephos	0.008	1	–	–	1	0.2	0.2	ND	–	–	1	0.1	0.1	1	0.05	0.05
Profenofos	0.01	5	34.4	53.4	1	–	0.6	12	322.9	406.4	3	3.2	85.7	1	–	159.1
Pirimiphosmethyl	0.02	ND	–	–	ND	–	–	ND	–	–	ND	–	–	1	0.2	0.2
Fenitrothion	0.01	6	148.4	495.1	3	40.4	65.0	5	63.1	289.1	8	168.1	490.7	6	180.7	505.6
Carbamates																
Aminocarb	0.02	7	0.06	0.1	3	0.1	22.4	4	0.06	0.07	12	0.2	1.7	7	0.1	0.1
Methomyl	0.03	8	0.4	0.5	4	0.3	0.4	7	0.3	0.3	6	0.1	0.1	9	0.2	0.3
Aldicarbfragment	0.01	4	0.2	0.3	2	0.05	0.5	5	0.3	0.4	3	0.3	0.3	4	0.06	0.07
Pirimicarb	0.03	9	0.2	0.6	9	0.2	0.7	6	0.07	0.4	5	0.03	0.4	2	-	-
Dioxacarb	0.01	2	45.3	69.2	4	14.7	52.7	2	39.9	59.4	2	19.2	79.5	2	30.4	104.5
Carbaryl	0.008	2	–	0.01	2	0.07	0.1	1	–	0.09	1	–	0.05	3	0.2	0.2
Carbofuran	0.009	2	0.1	0.8	2	0.009	0.1	2	0.06	0.06	1	–	–	1	–	1.0
Alanycarb	0.01	3	1.6	1.6	2	0.9	0.9	13	209.4	209.4	4	94.2	94.2	4	47.0	47.0
Benfuracarb	0.05	3	7.1	7.1	ND	–	–	2	48.7	48.7	5	878.5	878.5	2	52.7	52.7
Methiocarb	0.04	6	0.2	0.02	5	0.07	0.07	2	0.06	0.06	5	0.3	0.3	1	0.01	0.01
Neonicotinoids																
Imidacloprid	0.03	13	4.9	5.0	12	5.3	7.5	10	2.3	3.1	7	2.2	8.1	6	1.7	3.0
Acetamiprid	0.02	3	8.1	110.1	6	7.9	47.2	12	21.4	126.6	7	54.3	58.2	2	12.2	18.4
Thiacloprid	0.01	ND	–	–	2	0.03	0.2	1	–	0.06	ND	–	–	ND	–	–
Pyrethriods																
Bifenthrin	0.02	5	0.9	2.5	7	0.3	0.3	11	2.0	6.8	5	0.7	0.8	3	0.2	0.2
Lambda-Cyhalothrin	0.02	16	0.9	1.0	12	0.7	1.8	10	0.8	2.5	13	0.9	0.9	13	0.9	1.6
Deltamethrin	0.01	ND	–	–	ND	–	–	1	–	0.06	1	–	1.8	1	–	0.2
Cypermethrin	0.01	8	2.0	2.0	2	0.02	0.2	9	0.9	15.6	6	0.8	12.1	8	1.0	10.4

(Continued)

Table 5. (Continued)

PESTICIDE	LOD (μG/KG)	WATER MELON			PASSION FRUIT			TOMATO			CABBAGE			EGG PLANT		
		DF	P95	MAX	DF	P95	MAX	DF	P95	MAX	DF	P95	MAX	DF	P95	MAX
Others																
Carbendazim	0.02	5	0.1	0.1	4	1.0	3.2	2	-	0.03	4	0.07	4.2	1	-	0.01
Imazalil	0.01	7	2.1	7.6	6	3.9	3.9	7	0.7	3.0	10	1.7	1.7	4	2.2	5.9
Metazachlor	0.01	4	0.1	0.2	7	0.1	0.8	14	0.3	1.0	9	0.1	0.2	8	0.1	0.2
Metalaxyl	0.02	ND	–	–	1	–	0.1	1	–	1.4	ND	–	–	ND	–	–
Azaconazole	0.006	4	0.07	0.07	3	1.6	1.6	3	0.05	0.05	3	0.1	0.1	1	0.4	0.4
Clomazone	0.007	ND	–	–	ND	–	–	1	0.05	0.05	ND	–	–	ND	–	–
Azoxystrobin	0.007	ND	–	–	ND	–	–	2	66.5	66.5	1	50.9	50.9	2	33.0	33.0
Pyrimethanil	0.02	8	0.7	0.7	8	0.5	0.5	9	0.4	0.4	8	0.6	0.6	5	0.4	0.4
Spirotetramat	0.02	5	0.5	0.5	1	0.07	0.07	7	1.0	1.0	4	0.1	0.1	3	0.07	0.07
Fenhexamid	0.01	2	205.6	205.6	5	493.7	493.7	ND	–	–	3	168.2	168.2	1	139.7	139.7
Fenarimol	0.01	8	2.7	2.7	6	1.9	1.9	5	0.6	0.6	4	4.6	4.6	12	3.0	3.0
Fluazifop	0.02	2	3.6	171.0	ND	–	–	ND	–	–	2	3.0	10.8	ND	–	–
Flufenoxuron	0.02	3	–	–	3	–	0.2	1	–	–	7	0.05	0.08	3	0.03	0.04
Pyriproxyfen	0.007	1	0.05	0.05	ND	–	–	ND	–	–	ND	–	–	ND	–	–
Quinoxyfen	0.03	3	0.2	0.2	2	0.5	0.5	2	0.5	0.5	ND	–	–	3	0.5	0.5
Proquinazid	0.01	ND	–	–	ND	–	–	4	8.0	8.0	1	4.3	4.3	1	1.5	1.5

Abbreviations: DF, detection frequency; LOD, limit of detection; Max, maximum concentration; ND, not detected; p95, 95th percentile.
[a]Mancozeb, Maneb, Metiran, Pronineb, Thiram and Zinam expressed in CS_2.

addition, our findings show the potential for contamination along the supply chain but of the farm. The use of pesticides during packing, transport, in restaurants and in homes to increase the self-life of fruit and vegetables, and resulting in contamination of food could also explain the increase in pesticide residue concentration.[70] Our finding are similar to study carried in Ghana which revealed that vegetable samples drawn from restaurants and streets had high pesticide residue concentrations than those from the farm and vice versa.[47] The study findings demonstrate that not all pesticide residues along the chain are from the farm.

Most of the detected pesticide residues were detected throughout the chain. Occurrence of the most frequently detected pesticides throughout the chain implies that either they were applied without observing the pre-harvest intervals or along the supply chain. Existence of the most frequently detected pesticides among all fruits and vegetable types could be as a result of growing the produce within the same farm and thus get contaminated through drift or application of the different pesticide across all the farms.[71]

Our findings have policy and research implications. The use of banned pesticide in fruit and vegetable production demonstrate the need for enforcement of respective regulations. In fact, the use of pesticide banned in other markets including the EU and USA who are Uganda's fruit and vegetable market also necessitates the need for field tests and review on the pesticides imported and used within the country to inform decision making. Our findings also demonstrate the need for development and implementation of a policy on national monitoring and surveillance of pesticide residues in foods especially in fruits and vegetables. This study is one of the first comprehensive assessments of pesticide residues in fruit and vegetables along the supply chain from farm to fork, providing any opportunity to understand how their concentrations change along the chain and provide a basis to assess dietary exposure in Uganda. So, there is need to study the trends of pesticide residues along the farm to fork chain while following a particular food type from one point to another throughout the web. There is also need to study the use and occurrence of multiple pesticide residues in fruits and vegetables. Given exposures to pesticides are associated with acute and chronic health effects,[72-75] in future analyses we will assess the human health risks to Ugandans from pesticide residues in produce.

Conclusion

Our findings demonstrate occurrence of pesticide residues in commonly consumed fruits and vegetables in Uganda. Farmers use multiple classes of pesticide for fruit and vegetable production including organophosphates, carbamates, pyrethroids, dithiocarbamates and neonicotinoids. We found that many active ingredients from these classes, including, Propotamophos, Acephate, Fonofos, Monocrotophos, Dichlorvos, Aminocarb, Methomyl, Pirimicarb, Imidacloprid and Lambda-cyhalothrin, were commonly present in produce ready for human consumption. In future analyses we will evaluated the human health risks associated with dietary exposure to these pesticides. However, there is need to regularly monitor pesticides residues as well as sensitize stakeholders involved in food production and handling about proper pesticide use practices.

Authors' Note

This manuscript is looking at pesticides residues in fresh fruits and vegetables, an environmental contaminant that affects the health of individuals and society once they are exposed through consumption. It also assessed how the pesticide residue concentration reduce or increase as you move from farm to fork. Lastly, there are similar papers from Uganda that have been published in environmental health insights but didnot apply the farm to fork model.

Acknowledgement

The authors wish to thank farmers, market vendors, street vendors, restaurants and homes from whose premises study samples were collected. The authors would also like to thank the pesticide laboratory team at the Government Analytic Laboratory (GAL) especially Evarist Natugonza and Oscar Kibirango for their support during sample collection and analysis as well as Mr. Aggrey Atuhaire from Uganda National Association of Community and Occupational Health for his support with sampling.

Author Contributions

Conceived and designed the experiments: CS, AB, JCS and DG. Analysed the data: CS. Wrote the first draft of the manuscript: CS. Contributed to the writing of the manuscript: CS, AB, JCS, FS and DG. Agree with manuscript results and conclusions: CS, AB, JCS, FS and DG. Jointly developed the structure and arguments for the paper: CS, AB, JCS, FS and DG. Made critical revisions and approved final version: CS, AB, JCS, FS and DG. All authors reviewed and approved of the final manuscript.

Disclosure and Ethics

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.

Supplemental Material

Supplemental material for this article is available online.

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