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Monitoring of imidacloprid residues in fresh fruits and vegetables from the central parts of Jordan

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A R T I C L E I N F O

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A B S T R A C T

Imidacloprid pesticide is widely utilized in agriculture due to its effectiveness in controlling a broad spectrum of insect pests. However, its usage has raised concerns about potential environmental impacts, and requires careful monitoring and responsible application to ensure sustainable agricultural practices. Thus, Gas chromatography-mass spectrometry (GC-MS) was utilized to analyze imidacloprid in 300 vegetable and fruit samples obtained from 15 major wholesalers in four regions of Amman, Jordan's capital city. Among the examined samples, 39.7 % were found to be contaminated with imidacloprid residues. Imidacloprid levels in different edible fruits and vegetables ranged from less than the Limit of Quantification (LOQ) to 0.40 mg kg^{-1}. Significantly, eggplant and apples exhibited the highest average values (0.40 and 0.25 mg kg^{-1}, respectively). Lower levels were detected in bananas (0.04 mg kg^{-1}), potatoes (0.05 mg kg^{-1}), grapes (0.07 mg kg^{-1}), and cabbage (0.07 mg kg^{-1}). Imidacloprid was below the method detection limit (BD) in samples of okra, peaches, apricots, and carrots. Overall, 25 samples (8.3 %) exceeded the Codex maximum residue limit (MRL) for imidacloprid. Moreover, 8 out of the 300 samples (2.7 %) exceeded the MRL established by the Pest Management Regulatory Agency (PMRA). Notably, the fruits of eggplant and apple contained the highest residual levels (1.30 and 0.83 mg kg^{-1}, respectively), markedly exceeding the CODEX and PMRA MRLs. Additionally, the maximum detected imidacloprid residue concentration in bananas (0.25 mg kg^{-1}) was 500 % higher than the CODEX MRLs. The estimated average daily intake (EDI) of the Amman population varied from 0.00 to 0.144 μg kg^{-1} body weight day^{-1} across various products. The hazard index (HI) for imidacloprid ranged from 0.00 to 0.24, all of which were below unity in all samples (<1). In conclusion, this investigation reveals low HI levels of imidacloprid residues in commonly consumed fruits and vegetables. However, the significant presence of imidacloprid residues in some samples highlights the urgent need for comprehensive measures to limit potential health hazards to consumers.

1. Introduction

Rapid growth of the world population necessitates increased agricultural productivity, leading to widespread use of mechanization,

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fertilizers, and pesticides [1,2]. However, this development contributes to environmental pollution, posing risks to human health and the ecosystem due to pesticide and chemical fertilizer residues in air, soil, water, and agricultural products [1,3–6]. Despite their importance in controlling crop diseases and insects, careful consideration of their negative impacts is essential [7,8].

Insects are the most diverse and successful group of animals, capable of invading diverse environments, including agricultural fields. Over 10,000 insect species cause damage to major food crops, leading to an estimated annual loss rate of about 13.6 % worldwide [9]. As a result, insecticides constitute the largest portion of global pesticide usage, serving to enhance food and fiber production and prevent vector-borne diseases [9]. The annual global consumption of pesticides exceeds two million tons, with insecticides comprising 29.5 % of this total, ranking second after herbicides [10]. In Jordan, insecticides account for 27 % of total pesticide consumption, amounting to 1370 tons yr^{-1} [11]. On average, pesticides are applied approximately ten times per growing season [12]. Neonicotinoids, which are structurally similar to nicotine, constitute the most extensively employed class of insecticides for managing biting and sucking insects. Seven neonicotinoids (imidacloprid, acetamiprid, nitenpyram, thiamethoxam, thiacloprid, clothianidin and dinotefuran) make up approximately 17 % of the world insecticide market value [13,14]. Among this group, imidacloprid ($C_9H_{10}ClN_5O_2$) is the second most widely used insecticide globally. It acts as a systemic insecticide with translaminar action, functioning as an antagonist of postsynaptic nicotinic acetylcholine receptors [15].

Monitoring imidacloprid residues in vegetables and fruits at wholesale markets in Jordan is of great significance for many reasons. Firstly, imidacloprid is widely used in agriculture for its effectiveness in controlling pests that feed on plant foliage and sap [16,17]. However, concerns arise due to its systemic nature and prolonged persistence, potentially leading to contamination of agricultural produce, especially fresh fruits and vegetables, which are vital components of the human diet [13,17]. Ensuring safe levels of imidacloprid residues in these food items is crucial to protect consumer health and minimize adverse effects of pesticide exposure [16,18]. Secondly, Jordan's agricultural sector heavily relies on fruit and vegetable exports, making it crucial to comply with international standards and regulations regarding pesticide residues [7,12]. Many countries have established maximum residue limits (MRLs) for pesticides, including imidacloprid, in imported food items. Monitoring imidacloprid residues in wholesale markets ensures exported produce meets these MRLs, avoiding potential trade barriers and protecting Jordan's reputation in the global market [7,18].

Moreover, imidacloprid is known to be toxic to non-target organisms, including humans and wildlife [19]. Acute exposure can lead to symptoms like headaches and nausea whereas prolonged exposure may impact the nervous, endocrine, and immune systems [19,20].

Limited research has been conducted in Jordan to assess imidacloprid residues in various agricultural commodities. In a multi-residue assessment study, 158 fruit and vegetable samples produced in Jordan were analyzed for pesticide residues, revealing the presence of 22 different pesticides. Detectable pesticide residues were found in 85 samples, accounting for 54 % of the total. Among the detected samples, imidacloprid emerged as the second most identified pesticide, being present in 23 out of the 85 samples [7]. The researchers also noted that hot pepper, sweet pepper, and zucchini had values that exceeded the maximum residual limits. Philippe et al. [17] detected 14 pesticides at concentrations exceeding international MRLs in several Eastern Mediterranean countries, including Jordan. These compounds were all insecticides from different chemical classes. Among them, two are part of the neonicotinoid group: imidacloprid and thiacloprid. Imidacloprid appeared in 19 samples across 16 commodities, with concentrations above MRLs in 3 commodities. The highest recorded value was 1.2 mg kg^{-1} in cucumber [18].

Focusing specifically on the analysis of imidacloprid residues, rather than conducting a multiple pesticide residue analysis, allows for a more targeted approach [16,18,20]. Given its widespread use and potential risks, individual monitoring of imidacloprid helps to identify any instances of excessive contamination accurately and to pinpoint potential sources or specific agricultural practices that may contribute to higher residue levels [21–23]. Considering these factors, a comprehensive monitoring program for imidacloprid residues in fruits and vegetables at wholesale markets is essential to promote food safety, protect the environment, and ensure the sustainability of Jordan's agricultural sector. This study aims to contribute valuable data and insights that can aid in formulating effective pesticide management strategies and ensuring public health and environmental sustainability.

2. Materials and methods

2.1. Chemicals and reagents

The following solvents and reagents were used for pesticide residue analysis; 99 % 6-chloronicotinic acid ($C_6H_4ClNO_2$), 97 % sodium hydroxide (NaOH), 99 % anhydrous sodium sulfate (Na_2SO_4), 99 % potassium permanganate ($KMnO_4$), sodium-bisulfite ($NaHSO_3$), 99 % t-butylmethyl ether ($C_5H_{12}O$), Amberlite XAD-4 (20–60mesh), and N-methyl-N-(trimethylsilyl) trifluoroacetamide ($C_6H_{12}F_3NOSi$) were obtained from Sigma-Aldrich. (Germany). Additionally, methanol (99.9 %) and acetonitrile (99.9 %) were purchased from Merck, (Germany). The imidacloprid analytical standard was obtained from Bayer (Germany). Gases, especially Nitrogen and Helium (99.99 %), were obtained from Amman LPG Filling Gas Station in Jordan. The organic-free deionized water used in the analysis was obtained from Riedel de-Hean in Germany.

2.2. Sample collection

Analyzing imidacloprid residues in apples, bananas, grapes, apricot, peaches, watermelon, cantaloupe, strawberry, carrot, tomato, cucumber, potatoes, eggplant, zucchini, cauliflower, cabbage, bell pepper, green beans, okra, and spinach is crucial for ensuring the safety of Jordanians' food consumption. These crops are fundamental components of the local diet, commonly consumed by the population. Monitoring pesticide residues, especially imidacloprid, helps protect Jordanian consumers from potential health risks and ensures that the food they eat meets safety standards. For this purpose, a total of 300 samples of these locally produced fruits and vegetables were collected between 2019 and 2021. During the regular harvest seasons, samples were collected from 15 randomly selected wholesalers in four major regions of Jordan's capital city, Amman. Amman, constitutes 42 % of the total population of the Jordan. This highlights the city's significant demographic importance and reinforces the study's focus on the consumption of major fruits and vegetables by Amman's residents for food safety considerations. Fresh fruit and vegetable samples (1–2 kg each) of the 20 mentioned crops were collected, stored in sterile plastic bags, labeled, and transported in an icebox (4 °C) to the laboratory for analysis.

2.3. Sample extraction and analytical procedure

Gas chromatography is a highly prevalent and reliable technique employed for the analysis of volatile and semi-volatile compounds, owing to its high accuracy, versatility, and the availability of selective detectors for numerous pesticides [24]. For precise and specific detection of pesticides, gas chromatography/mass spectrometry (GC/MS) with selected ion monitoring (SIM) has been widely utilized for routine analysis of some ubiquitous environmental pollutants [25,26].

Subsample of collected fruits (200 g) were chopped and homogenized at high speed for 3 min. Fifty grams of the homogenized sample were immersed in a mixture of methanol: water (75 % v/v, 300 ml) for half an hour. After shaking and filtering the resulting mixture, additional methanol was added to bring the final volume to 500 ml in the filtrate. Next, a 100 ml aliquot was evaporated to 20 ml using the rotary evaporator at 60 °C. The resulting aliquot portions were then transferred to a to a pre-conditioned column packed with XAD- 4 resin (for water samples, 250 ml aliquot were concentrated to 20 ml before transferring to the column). The column was washed two times with methanol: water (75 % v/v, 20 ml), after which the retained compounds were eluted with methanol (100 ml). Subsequently, a vacuum rotary evaporator was used to concentrate the compounds into 1 ml followed by drying using a gentle stream of nitrogen.

According to Placke and Weber [27], imidacloprid and other derivatives containing the 6-chloropicolyl moieties were extracted in 1 ml concentrate and oxidized to 6-chloronicotinic acid through the following steps: The concentrate was diluted in 100 ml of water, and then an oxidizing solution containing 32 % NaOH and $KMnO_4$ (5 %, 50 ml–100 ml added to samples of hops) was added. The mixture was refluxed and stirred for 5 min, followed by the addition of 50 ml of water to the samples. The flask was cooled to 15 °C with agitation in an ice bath for 10 min. Subsequently, 10 % sulfuric acid (50 ml) was added, and 3 g of solid sodium bisulfite was added under cooling and agitation. Additional sulfuric acid was added to maintain a pH value of $\leq$1. The final extraction was performed using a solution of 150 ml *t*-butyl ether and the organic phase filtered through 30 g of anhydrous sodium sulfate and then dried in an evaporator. The extract was then dissolved in 2 ml of acetonitrile and a 250 μl aliquot of the solution was derivatized to 6-chloronicotinic acid trimethylsilyl ester by vigorously mixing with N-methyltrimethylsilyltrifluoroacetamide (MSTFA). A 1 μl aliquot was injected into the GC/MS under split-less mode.

Standard solutions of 6-chloronicotinic acid were prepared following the above-mentioned protocol, and their aliquots were injected prior to of the sample aliquots. The Placke and Weber analytical method [27] was subjected to validation prior to its utilization. Several quality control parameters were confirmed, and the results were found to be consistent with those reported by Placke and Weber [27]. The method detection limit (MDL) for the standard mixture ranged from 0.015 to 0.030 mg kg^{-1}, as determined through multiple dilutions (triplicate standard deviation of a blank produced using the same previously mentioned method). Additionally, the spike recovery was found to be in the range of 74–106 %.

The analysis of imidacloprid in samples was conducted using an Agilent 6890 series II GC, equipped with an auto-sampler injector 7683 series and a mass selective quadrupole detector, along with a DB-5 capillary column. Helium (99.999 %) served as the carrier gas, following at a rate of 1 ml min^{-1}. Sample injection (1 μl) was performed in splitless mode at an injector temperature of 260 °C. The oven temperature program initiated at 100 °C (held for 1 min), followed by a ramp to 180 °C at a rate of 15 °C min^{-1}, and then further increased to 300 °C at a rate of 30 °C min^{-1}, where it was held for 3 min. For quantification of 6-chloronicotionic acid-trimethylsilyl ester, the target ion was set to 214, and the qualifying ion to 170.

2.4. Calculation of pesticide residue intakes

Risk assessment involves comparing the detected pesticide residues with the estimated amounts of pesticides that can be consumed daily in foods or beverages without posing an appreciable risk to health. This method is known as acceptable daily Intake (ADI), set at 60 μg kg^{-1} bw^{-1} day^{-1} for imidacloprid by the Codex Alimentarius Commission [28]. The imidacloprid residue concentrations in all fruits and vegetable samples were determined using the arithmetic mean of all detected results. Furthermore, the estimated daily intake (EDI) of imidacloprid residue was calculated in accordance with international guidelines [29,30] using the following equation:

$$\mathrm{EDI} = \frac{\sum \mathrm{C} \times \mathrm{F}}{\mathrm{D} \times \mathrm{W}}$$

Where C represent the average pesticide (imidacloprid) concentration in each agricultural product (μg kg^{-1}), F is the average annual consumption of a food item per person (kg), D is the number of days in a year (365), and W is the average body weight used in the calculations based on international guidelines (60 kg).

To assess the long-term risks associated with pesticide residues, the hazard index (HI) was calculated using the following equation [31].

$$HI = \frac{EDI}{ADI} \times 100\%$$

Where EDI represents the estimated daily intake and ADI stands for the acceptable daily intake.

3. Results and discussion

3.1. Imidacloprid residues in edible parts

Table 1 displays the concentrations of imidacloprid residues detected in the edible parts of various fruits and vegetables obtained from different retail markets. Out of the 300 samples tested, detection frequencies varied widely, ranging from % 0–100 %, across the 15 representative samples for each product. Seven samples had detection frequencies exceeding 50 %. Notably, bell pepper and cauliflower exhibited detection frequency of 53 % each while apple and cantaloupe showed 60 % detection frequency each. The detection frequency was even higher for cucumber (73 %), zucchini (80 %), and eggplant (100 %). Conversely, banana and green beans had relatively low detection frequency of 20 %, while potatoes, tomato, and cabbage recorded detection frequencies of 27 %, 33 %, and 33 % respectively. Notably, no imidacloprid residues were detected in apricot, peaches, carrot, and okra samples.

The levels of imidacloprid in the edible parts of various fruits and vegetables ranged from less than LOQ to 0.40 mg kg^{-1}. Among the different samples, eggplants and apples exhibited the highest average concentrations, measuring 0.40 mg kg^{-1}, and 0.25 mg kg^{-1}, respectively. Conversely, lower concentrations were observed in bananas (0.04 mg kg^{-1}), potatoes (0.05 mg kg^{-1}), grapes, and cabbage (0.07 mg kg^{-1}). Notably, imidacloprid residues were below the limit of detection in samples of apricot, peaches, carrots, and okra.

These findings align with similar reports from other studies, which have also indicated high concentrations of imidacloprid in peaches, watermelons, potatoes, grapes, and Okra [16,32]. In the case of Jordan, the elevated levels of imidacloprid residues in apple and eggplant products could be attributed to their frequent use in controlling endemic pests such as flatheaded apple tree borer, whiteflies and aphids that infect eggplant seedlings, resulting in significant losses for farmers [33–35]. The intensive application of imidacloprid as a pest management strategy may contribute to the observed higher residues in these fruit and vegetable samples.

3.2. Imidacloprid maximum residual limits in edible parts

Pesticides are extensively used in the global agricultural sector; however, excessive usage can result in severe environmental problems and pose significant chronic health risks for humans [36]. In the 1960s, the Food and Agricultural Organization (FAO) and the World Health Organization (WHO) collaborated to establish the Codex Alimentarius Commission, responsible for defining standardized food regulations and national Maximum Residue Limit (MRL) for pesticides [37,38]. Consequently, many countries have developed laws and regulations to control pesticide application and set MRLs for the residues in food products, such as the Canada's Pest Management Regulatory Agency (PMRA) [39]. In this study, CODEX and PMRA were employed to evaluate MRLs of imidacloprid in the analyzed fruit and vegetable samples, with the results presented in Table 2.

Out of the total 300 samples analyzed, 25 samples (8.3 %) exceeded the MRL established by Codex [37] for imidacloprid residue,

Table 1
Mean and range values of imidacloprid residues and number of samples with detectable residues in edible parts of 20 different fruits and vegetables crops collected from different wholesales markets in Amman, Jordan during 2019–2021. Mean values were recorded ± standard deviation.

Fruit/Vegetable	Mean ± Sd (mg kg^{-1})	Range (Min-Max)	Number of Samples analyzed	No. of samples with detectable residues and their (%)
Apples	0.25 ± 0.21	0.19–0.83	15	9 (60 %)
Banana	0.04 ± 0.05	0.15–0.25	15	3 (20 %)
Grapes	0.07 ± 0.09	0.08–0.32	15	6 (40 %)
Apricot	BD	–	15	0
Peaches	BD	–	15	0
Watermelon	0.12 ± 0.18	0.06–0.56	15	7 (46.7 %)
Cantaloupe	0.18 ± 0.19	0.07–0.61	15	9 (60 %)
Strawberry	0.10 ± 0.08	0.09–0.33	15	7 (46.7 %)
Carrot	BD	–	15	0
Tomato	0.11 ± 0.23	0.07–0.61	15	5 (33.3 %)
Cucumber	0.18 ± 0.18	0.06–0.62	15	11 (73.3 %)
Potatoes	0.05 ± 0.13	0.07–0.34	15	4 (26.7 %)
Eggplant	0.40 ± 0.33	0.08–1.30	15	15 (100 %)
Zucchini	0.18 ± 0.15	0.06–0.56	15	12 (80 %)
Cauliflower	0.18 ± 0.18	0.09–0.62	15	8 (53.3 %)
Cabbage	0.07 ± 0.10	0.09–0.36	15	5 (33.3 %)
Bell pepper	0.12 ± 0.12	0.06–0.42	15	8 (53.3 %)
Green beans	0.03 ± 0.14	0.06–0.34	15	3 (20 %)
Okra	BD	–	15	0
Spinach	0.09 ± 0.13	0.06–0.41	15	7 (46.7 %)
Total			300	119 (39.7 %)

*Below method detection (BD) stands for values lower than LOD of imidacloprid which was 0.03 mg kg^{-1}.

while 8 samples (2.7 %) exceeded the MRL set by PMRA [39]. Variable concentrations of imidacloprid residue were observed across different samples, with the highest levels found in the fruits of eggplants and apples (1.30 mg kg^{-1} and 0.83 mg kg^{-1}, respectively) surpassing both CODEX and PMRA MRLs by a considerable margin. In the case of bananas, the maximum detected imidacloprid residue concentration (0.25 mg kg^{-1}) exceeded the CODEX MRL by 500 %. However, for the rest of the products, the maximum imidacloprid residues did not reach harmful levels and were around or below the CODEX and PMRA MRLs.

Understanding that maximum residue limits (MRLs) guide pesticide levels in food, based on authorized practices, is crucial. MRLs consistently stay below levels clearly considered safe for consumption [40]. Importantly, MRLs differ from precise safety limits [12]. Comprehensive safety evaluations, such as acceptable daily intake for short-term exposure or acute reference dose, provide a broader safety perspective. MRLs also comply with legal mandates in most countries, adding to their contextual importance [40]. Nevertheless, the results concerning imidacloprid residues in certain products, such as eggplant, grapes, and apples, are concerning. The presence of residues above the MRLs indicates potentially imprudent use of insecticides containing imidacloprid, calling for corrective agricultural practices among farmers. Such mismanagement can increase the risk of harmful health effects on consumers. Moreover, excessive pesticide use can lead to pesticide resistance, posing further challenges to pest control and agriculture sustainability [41].

3.3. Risk assessment for imidacloprid intake

Numerous countries have implemented legislation to ensure quality control and monitoring of pesticides residues in food, requiring compliance with certified maximum residue limits to protect consumer health (WHO 2003) [42]. Evaluation of the toxicological impact of human exposure to imidacloprid residues were evaluated in this study. Table 3 presents a comparison between the estimated contribution of various consumed fruits and vegetables (EDI) according to the Jordanian Department of Statistics [11] and the acceptable daily intakes (ADIs) established by the FAO/WHO Organization [43].

The data reveal that imidacloprid intakes from fruits and vegetable samples were substantially lower than the ADIs, indicating that the exposure level to imidacloprid residues was well below the threshold posing any health risk (Table 3). Among the tested samples, eggplant demonstrated the highest exposure value (400 μg kg^{-1}), followed by apples (250 μg kg^{-1}), cantaloupe, zucchini, cucumber, and cauliflower (180 μg kg^{-1}). Conversely, potatoes, spinach, green beans, cabbage, bananas and grapes had exposure levels below 100 μg kg^{-1}. Notably, apricots, peaches, carrots, and okra exhibited no detectable imidacloprid residues. In every case, imidacloprid concentrations were found to be lower than the ADI established by the Codex Alimentarius Commission [43], further reinforcing the safety of the analyzed samples.

In this study, the estimated daily intakes (EDIs) of various fruits and vegetables ranged from 0.00 to 0.144 μg kg^{-1} body weight day^{-1} with hazard index (HI) ranging from 0.00 to 0.25 % (Table 3). Notably, due to their frequent inclusion in most Jordanian meals, tomatoes, cucumbers, and eggplants exhibited the highest EDIs (>0.118 μg kg^{-1} body weight day^{-1}) and corresponding HI values (>0.197). However, these results suggest that the lifetime consumption of these vegetables and fruits does not pose a health risk for consumers, as the HI values for all the residues were less than one [44,45]. Nevertheless, the current study reveals significant levels of imidacloprid residues in 39.7 % of the examined fruit and vegetable samples. A comprehensive study focusing on the occurrence of pesticides residues in the eastern Mediterranean region indicated the presence of several types of pesticides residues in several agricultural commodities, which are often more susceptible to pest infestation [7,46]. This study on imidacloprid residues in vegetables and fruits demonstrates several strengths. The research employed careful sampling process, considering specific regions and

Table 2
The Codex (2005) [32] and Canadian [34] imidacloprid maximum residue limits (mg kg^{-1}) in edible parts of 20 different fruits and vegetables used in this study and number of samples with levels above MRL.

Fruit/vegetables	Codex MRL	No. of Samples with residue < Codex MRL	Canadian MRL	No. of samples with residue < Canadian MRL
Apple	0.5	3	0.6	3
Banana	0.05	3	–	–
Grape	1.0	0	1.5	0
Apricot	–	–	3.0	0
Peaches	0.5	0	3.0	0
Watermelon	0.2	4	0.5	1
Cantaloupe	–	–	0.5	2
Strawberry	0.5	0	0.5	0
Carrot	–	–	0.4	0
Tomato	0.5	2	1.0	0
Cucumber	1.0	0	0.5	1
Potatoes	0.5	0	0.4	0
Eggplant	0.2	11	1.0	1
Zucchini	–	–	–	–
Cauliflower	0.5	2	–	–
Cabbage	0.5	0	–	–
Bell pepper	–	–	1.0	0
Green beans	2.0	0	–	–
Okra	–	–	1.0	0
Spinach	–	–	3.5	0

***MRL** Maximum Residue Limits in (mg kg^{-1}).

Table 3
Mean imidacloprid exposure values (μg/kg), annual fruits intake (F; kg person $^{-1}$ yr^{-1}), estimated daily intakes (EDI; μg kg^{-1} bw day^{-1}) and hazard index (HI; %) of imidacloprid in different fruit and vegetable samples.

Fruit/Vegetable	Mean μg/kg	(F) (kg person $^{-1}$ yr^{-1})	EDI (μg kg^{-1} bw day^{-1})	Hazard index (%)
Apples	250	7.37	0.084	0.140
Banana	40	10.00	0.018	0.030
Grapes	70	2.87	0.009	0.015
Apricot	0	–	0	0
Peaches	0	–	0	0
Watermelon	120	7.94	0.043	0.072
Cantaloupe	180	2.44	0.020	0.033
Strawberry	100	0.49	0.002	0.003
Carrot	0	–	0	0
Tomato	110	28.69	0.144	0.240
Cucumber	180	14.42	0.118	0.197
Potatoes	50	18.24	0.042	0.069
Eggplant	400	6.58	0.120	0.200
Zucchini	180	4.64	0.038	0.063
Cauliflower	180	4.26	0.035	0.058
Cabbage	70	1.73	0.006	0.010
Bell pepper	120	3.20	0.017	0.028
Green beans	30	0.44	0.001	0.001
Okra	0	–	0	0
Spinach	90	1.03	0.004	0.007

*F = Mean annual intake of the commodity per person; EDI (μg/kg bw daily) According to (Jordanian Department of Statistics [10]; ADI (60 μg kg^{-1} body weight day^{-1}) According to Codex Alimentarius Commission (FAO/WHO, 2004) [38].

seasons, which significantly contributed to our understanding of contamination levels. Despite the relatively small sample size, the study's findings provide valuable insights. The use of GC/MS as the analytical method ensures reliable and sensitive detection of pesticide residues [16,24]. Furthermore, the study raises awareness of potential risks associated with imidacloprid residues in fresh produce, highlighting the need for better food safety practices. The results serve as a foundation for future research and underscore the significance of continuous monitoring to ensure safer agricultural commodities for consumers. However, some limitations need to be acknowledged and addressed in future work. The sample size used in the study, although representative within the selected regions, may have been relatively small, potentially limiting the statistical power and precision of the findings. Additionally, the analytical method utilized, GC/MS, raises environmental concerns due to its reliance on hazardous materials and the generation of significant waste, including used solvents, contaminated filters, and expired standards [47,48]. Moreover, the lack of information regarding pre-harvest intervals for the tested produce items raises questions about the timing of pesticide application and its impact on residue levels. These combined limitations emphasize the need for further research using more comprehensive sampling strategies, larger sample sizes, and advanced analytical techniques to obtain a more accurate and representative assessment of imidacloprid residues in vegetables and fruits.

4. Conclusion

This study has shed light on the presence of imidacloprid residues in a significant proportion of fruits and vegetable samples, with 39.7 % showing contamination. The detected concentrations were below the maximum residue limit. However, it's important to note the high exposure levels in certain tested produce. This is especially significant because these items are often consumed fresh, without undergoing cooking processes that could reduce pesticide residues. The potential hazard index associated with the consumption of contaminated fruits and vegetables, particularly in large quantities, raises concerns about the cumulative effects of exposure to multiple pesticides present in meals simultaneously. This calls for urgent attention to food safety and the need for proper cleaning and washing practices before consuming these products.

Therefore, it is highly recommended to establish continuous monitoring of imidacloprid residues in agricultural commodities and environmental resources such as soil and water at the national level. This monitoring should be carried out in line with good agricultural practices and judicious pesticide use to mitigate potential risks to human health. Emphasis should be placed on crops with high hazard index values, such as eggplants and apples, to ensure the safety of consumers. By implementing these measures, we can take proactive steps to reduce the potential adverse effects of pesticide residues in our food supply and protect consumers.

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Data availability

Data will be available on request. Interested parties are invited to contact the first author or corresponding author directly to request access to this information.

CRediT authorship contribution statement

Jehad S. Al-Hawadi: Conceptualization, Data curation, Formal analysis, Funding acquisition, Writing – original draft, Investigation, Methodology. **Rabea S. Al-Sayaydeh:** Conceptualization, Formal analysis, Methodology, Resources, Writing – original draft, Writing – review & editing. **Ziad B. Al-Rawashdeh:** Investigation, Resources, Writing – review & editing, Methodology. **Jamal Y. Ayad:** Formal analysis, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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