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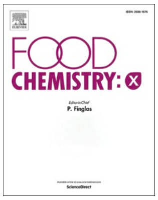

Organophosphorus pesticide contaminants in fruits and vegetables: A *meta*-analysis

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ABSTRACT

The worldwide demand for organophosphorus pesticides (OPs) in food production has raised concerns about pesticide residues. Meta-analysis, proven effective in assessing contaminants like aflatoxins and organotin compounds, is applied here to comprehensively study OP contamination in fresh fruits and vegetables. Employing Comprehensive Meta-Analysis V3.0 software, we meticulously examined 24 relevant articles encompassing 69,467 data points. Our findings revealed that while the residual concentrations of OPs (such as chlorpyrifos and profenofos) in most fruits and vegetables have typically met international or national safety standards, including Codex Alimentarius Commission, European Union, British, and Chinese standards, there are some instances in which the maximum residue limits have been exceeded, posing safety risks. Therefore, significant efforts are required to maintain residual OP contamination at safe concentrations.

1. Introduction

With the rapid growth of the global population, there is an increasing demand for food worldwide. However, climate change, including extreme temperatures, droughts, and heavy rainfall caused by greenhouse gas emissions, is worsening agricultural decline and posing a severe threat to global food security (Sweileh, 2020). Pesticides are the most effective means of defence against agricultural diseases and thus the key to securing the global food supply. According to the United Nations Food and Agriculture Organization (FAO), although the global use of pesticides has stabilised in recent years, the total consumption of pesticides in 2020 was projected to reach approximately 2.7 million tons, a 50 % increase compared with the 1990 s (FAO, 2022a). Organophosphorus pesticides (OPs) are a classic and widely used type of pesticide, with up to 2 million tons used annually worldwide, representing approximately 40 % of total global pesticide usage (Cioffi et al., 2021). However, concerns persist over pesticide residues arising from excessive usage, due to pesticides' impacts on human health and the environment. A study by Bodeker based on the World Health Organization (WHO) Mortality Database found that approximately 44 % of farmers globally are exposed to unsafe pesticide concentrations each year, resulting in approximately 38,500 cases of acute pesticide poisoning and 11,000 fatalities (Boedeker et al., 2020).

Fruits and vegetables are highly susceptible to pesticide contamination, particularly with OPs, which often leads to pesticide residues in fruits and vegetables exceeding the limits (Chung, 2017). This susceptibility can be attributed to the significant role these crops play in global agriculture. According to the FAO's 2022 World Food and Agricultural Statistics Yearbook, fruits and vegetables accounted for approximately 20 % of total global agricultural production and 37 % of the total agricultural output value in 2020, making them the second-most important agricultural products after cereals (FAO, 2022b). Additionally, fruits and vegetables have the highest export value among agricultural products (FAO, 2022a). Furthermore, due to fruits and vegetables having shorter growth cycles and freshness periods than grains, there is a greater chance of residual OPs persisting in fruits and vegetables on the market beyond their designated safety period (Chung, 2017). This increases the risk of OP poisoning and other food safety concerns.

As a result, concern about pesticide residues has gained considerable traction among international organisations, national government agencies, and the academic community (Tang et al., 2021). They have

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addressed this concern by undertaking a range of management, monitoring, and research initiatives to ensure that pesticide residues are maintained at safe concentrations.

At the global level, the FAO and the WHO jointly adopted the International Code of Conduct on Pesticide Management in 2013. This code governs pesticide use, registration, testing, and various behavioural aspects to ensure adherence to safe residue concentrations. Additionally, the Codex Alimentarius Commission (CAC) and its subsidiary Codex Committee on Pesticide Residues (CCPR) have formulated international standards for maximum residue limits (MRLs) of pesticides in different types of food. These standards play a crucial role in international food trade by guiding the determination of residual pesticide concentrations. At a national level, the United Kingdom and China and countries in the European Union have implemented specific pesticide management policies and MRL standards for pesticides in food (Farooq et al., 2022). Additionally, regulatory authorities responsible for food safety, such as those in the United States, regularly test concentrations of pesticide residues in domestically produced food and periodically publish reports.

In the academic field, researchers have long been dedicated to estimating pesticide-use levels and investigating pesticide safety hazards worldwide. For example, Tang et al. (2021) utilised a spatially explicit environmental model and global pesticide application data to estimate the environmental pollution risk caused by 92 active ingredients in pesticides used in 168 countries. Their findings indicate that approximately 64 % of global agricultural land (~24.5 million km^2) is at risk of pesticide pollution from at least one active ingredient, with 31 % facing a high risk. Moreover, toxicological studies of different types of pesticides have provided crucial scientific support that has enabled countries and international organisations to establish guidelines on maximum residual concentration of pesticides in food. Furthermore, systematic research on pesticide stability has offered valuable insights that have promoted the prudent use of pesticides and the use of low-toxicity and easily degradable pesticides (Maggi et al., 2023). However, despite these efforts, the problem of pesticide residues remains challenging worldwide due to the increased use of pesticides driven by global food demand.

Recently, *meta*-analyses have proven highly successful for the comprehensive statistical analysis of various food contaminants (Hunter & Schmidt, 1991), such as aflatoxins, and organotin compounds, in diverse food items, such as milk, and fish (Abyaneh et al., 2020). These studies serve as valuable references for monitoring contaminant concentrations in food and contribute significantly to our understanding of contamination patterns and trends across various countries and regions. Literature-based *meta*-analyses provide a multidimensional view of residual pesticide concentrations in a more diverse range of samples than those examined in pesticide monitoring reports issued by governmental departments in various countries (Ntakiyisumba et al., 2023). Moreover, due to significant between-country variation in sample types and MRLs, literature-based *meta*-analyses draw from a wide geographical and sample pool, thereby facilitating a more comprehensive comparative analysis than other approaches. Therefore, the primary objective of this *meta*-analysis was to examine residual OP concentrations in fresh fruit and vegetable samples in eligible studies around the world. This analysis integrates data from various countries, enabling a comprehensive assessment of OP residues and pollution levels. It could serve as a valuable reference for monitoring and managing OP contamination in food, which could contribute to reducing food safety risks stemming from these residues.

2. Materials and methods

2.1. Data sources and search strategy

The literature search was conducted on ISI Web of Science, Springer, and Science Direct from inception to April 3rd, 2023. And the following keywords were utilized to collect the related studies: ("organophosphorus pesticide" OR "OPs") AND ("fruit" OR "vegetable") AND ("contamination" OR "pollution") AND "detection".

2.2. Eligible criteria for inclusion and exclusion

Initially, we excluded categories such as book chapters and meeting conferences, narrowing our focus to articles only. After removing the duplicated studies, we performed the first screening by carefully reading the abstract of each article and eliminating any irrelevant papers. Following that, we downloaded the remaining articles and conducted a secondary screening by thoroughly checking their full-text articles, using the criteria described below. Notably, the evaluation process involved the participation of two researchers, and disagreements were resolved through the decision of the third researcher. Inclusion criteria were: (1) availability of full-text articles; (2) original research studies; (3) reporting the mean ± SD of the detective OPs or providing required data for calculating these values; (4) reporting the sample size; (5) publication from 2013 to 2023; (6) published in English language. Exclusion criteria were: (1) samples were neither fruits nor vegetables; (2) unclear reports with insufficient data (e.g.: lacking analytical method, unclear sample size); (3) reporting only recovery results; (4) detected pesticide were not organophosphorus; (5) did not meet included criteria.

2.3. Data collection

Data extraction from the selected studies included the following information: name of the first author, year of publication, sample type (specific fruits and vegetables detected), sample size, sample source, detection method, type of detected organophosphates (OPs), and mean ± SD (μg/kg) values.

Furthermore, the collected data based on top ten OPs with the highest detection frequency in eligible studies (namely chlorpyrifos, profenofos, dimethoate, acephate, methamidophos, triazophos, omethoate, diazinon, fenitrothion, and phorate) were divided into different subgroups by the following variables: (1) sample site (country), including the United Arab Emirates (UAE), China, Iran, Nigeria, Ghana, India, etc.; (2) sample type, including root vegetables, leafy vegetables, fruit vegetables, fruits, and beans.

2.4. Meta analysis

As illustrated in Table 1, 24 eligible studies (69,467 data) were included in this *meta*-analysis, eventually. All *meta*-analyses were conducted using the Comprehensive Meta Analysis V3.0 software. The contamination level of OPs in each study group and subgroup was estimated as pooled mean with 95 % confidence intervals (CI). In addition, I^2 statistics were calculated to evaluate the heterogeneity. Based on previous research, the random effect model was used to estimate the mean contamination and 95 % CI of OPs. Conversely, the fixed effect model was applied.

3. Results

3.1. Study selection

As shown in Fig. 1, 7,235 records were initially identified, and after removing 4,635 duplicates, 2,600 records remained. Subsequently, the records of 652 reviews, 160 conference papers, and 33 book chapters were excluded, leaving 1,755 records for screening based on a thorough assessment of titles and abstracts. This process afforded 899 articles that focused on contamination by OPs in fruits or vegetables. Each article was carefully checked against the inclusion and exclusion criteria (section 2.2). Ultimately, 24 articles, comprising 69,467 data points, were included in this *meta*-analysis and their characteristics are summarised

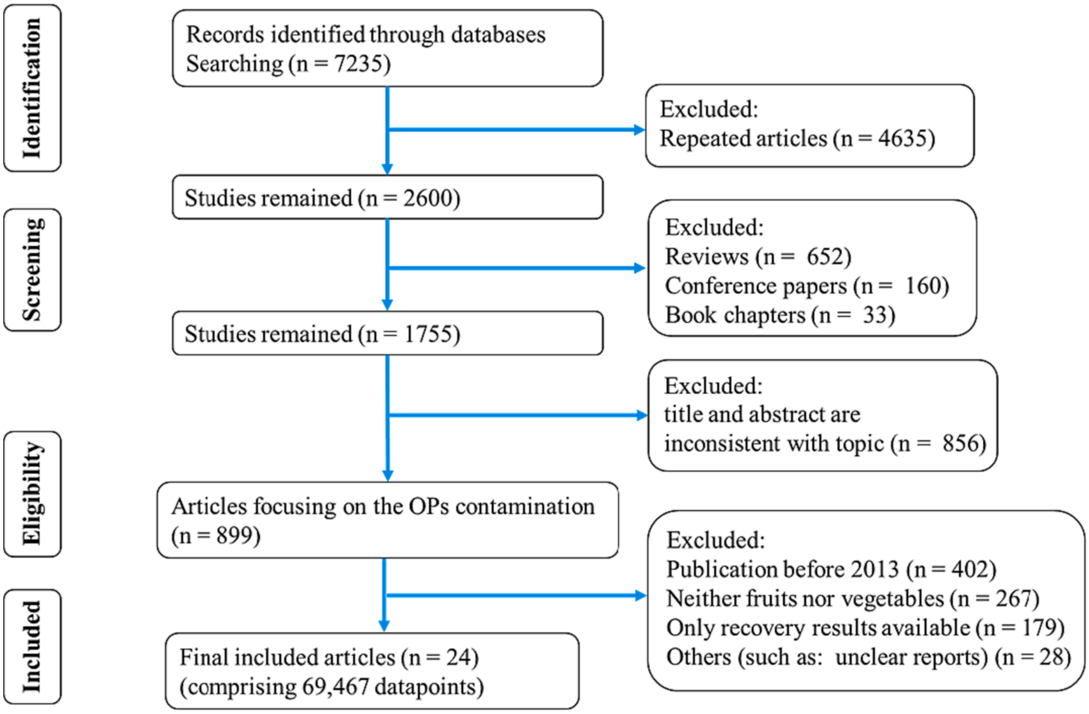

Fig. 1. Flow diagram of selection in *meta*-analysis.

in Table 1.

3.2. Study characteristics

3.2.1. Detection methods

Table 1 illustrates the various detection methods that had been used in the studies described in the 24 eligible articles. Twenty-nine detection methods were identified, as a few studies had employed two different methods. These methods were broadly classified into four categories. The most frequently used methods were gas chromatography-based methods, which accounted for 75.9 % (22/28) of the methods. These comprised gas chromatography-pulsed flame photometric detector methods, which accounted for 13.8 % (4/28) of the methods; gas chromatography-nitrogen-phosphorus detector and gas chromatography-pulsed flame photometric detector methods, which each accounted for 10.3 % (3/28) of the methods; gas chromatography-mass spectrometry methods, which accounted for 24.1 % (7/28) of the methods; and gas chromatography-tandem mass spectrometry methods, which accounted for 17.2 % (5/28) of the methods. The second-most frequently used methods were liquid chromatography-tandem mass spectrometry methods, which accounted for 17.2 % (5/28) of the methods. Other methods, such as enzyme-linked immunosorbent assays (ELISAs) (3.5 %, 1/28) and electrochemical sensor methods (3.5 %, 1/28), were less frequently used. These results demonstrate that despite the rapid development of novel OP-detection methods, such as ELISAs and electrochemical sensor-based methods, which enable ultra-sensitive detection of OPs at concentrations as low as 1×10^{-9}–1×10^{-12} mol/L (Yin et al., 2021), conventional gas chromatography/liquid chromatography-based methods remain the most established and widely used approaches for OP detection. These methods are also endorsed and recommended by most countries and international organisations worldwide.

3.2.2. Types of the detected OPs

As shown in Table S1, the 10 most commonly detected OPs types were: chlorpyrifos (12.0 %, 8,304/69,467), profenofos (9.8 %, 6,841/69,467), dimethoate (9.3 %, 6,467/69,467), acephate (9.0 %, 6,237/69,467), methamidophos (8.8 %, 6,105/69,467), triazophos (7.8 %, 5,417/69,647), omethoate (7.0 %, 4,837/69,467), diazinon (3.8 %, 2,623/69,467), fenitrothion (3.0 %, 2,061/69,467), and phorate (2.7 %, 1,842/69,467).

3.2.3. Sample source (site)

As shown in Table S2, the fruit and vegetable samples included in the *meta*-analysis database (69,467 data), were collected from the four main regions: the Middle East (65.2 %, 45,297/69,467) > Africa (18.2 %, 12,666/69,467) > Asia (16.3 %, 11,319/69,467) > America (0.3 %, 185/69,467).

Moreover, these samples were found across a total of 13 countries, and the six countries with the highest detection frequencies were as follows: UAE, accounting for 54.1 % (37,582/69,467) of the samples; China at 11.1 % (7,711/69,467); Iran at 11.0 % (7,665/69,467); Ghana at 10.0 % (6,916/69,467); Nigeria at 8.2 % (5,700/69,647); and India at 4.8 % (3,331/69,467).

3.2.4. Sample type

As illustrated in Table S3 and Table S4, among the total sample size of 69,467 collected from the included articles, 77 varieties of fruits and vegetables were included. These varieties could be divided into five categories (details could be attached at Supplementary Material), namely fruit vegetables (42.0 %, 29,163/69,467), fruits (41.1 %, 28,570/69,647), beans (6.4 %, 4,422/69,647), leafy vegetables (5.6 %, 3,915/69,467), and root vegetables (4.9 %, 3,397/69,467).

3.3. Estimated mean concentrations of OPs in samples from different countries

Additionally, we carried out a subgroup analysis on the ten OPs with the highest detection frequency, with a particular emphasis on the samples' geographical sources from different countries (Table 2).

Chlorpyrifos was found in samples from ten countries, with an estimated mean of 14.43 μg/kg (95 % CI [14.00, 14.85]). Among these, chlorpyrifos was detected in the highest quantity of samples from the United Arab Emirates (UAE) ($M = 99.09$ μg/kg, 95 % CI [75.70,

Table 1
Characteristics of the eligible articles included in this *meta*-analysis.

	Study characteristics		Sampling characteristics				Detection method	Reference
	Year	Country (region)	Sample type	OPs type	Sample size	Positive sample size		
1	2013	China (Shaanxi)	spinach, cucumber, pepper, etc.	chlorpyrifos, dimethoate, omethoate, etc.	505	52	GC–FPD	(Wang et al., 2013)
2	2023	Ethiopia (Mettu)	tomato	profenofos	50	5	GC–MS	(Wondimu and Geletu, 2023)
3	2016	China (Changchun)	cucumber, pepper, eggplant, etc.	dichlorvos, omethoate, phorate, etc.	2068	683	GC–FPD	(Yu et al., 2016)
4	2015	China (Shandong)	cucumber	triazophos, chlorpyrifos-methyl, diazinon, etc.	200	6	ELISA	(Zhao et al., 2015)
5	2022	China (Jiangsu)	potato, garlic, spinach, etc.	phoxim	18	18	electrochemical sensors	(Su et al., 2022)
6	2021	Iran (Khuzestan, Kerman, Bushehr, etc.)	dates	chlorpyrifos, dimethoate, diazinon, etc.	7560	7560	GC–MS	(Taghizadeh et al., 2021)
7	2019	India (Nilgiris)	potato, cabbage, carrot, etc.	quinathion, chlorpyrifos, malathion, etc.	3295	1415	LC–MS/MS	(Narenderan et al., 2019)
8	2016	Ghana (Nkrankwanta, Diabaa, Krakrom, etc.)	cocoa bean	diazinon, chlorpyrifos, pirimphos-methyl	96	62	GC–PFPD	(Okoffo et al., 2016)
9	2022	Nigeria (Enugu and Lagos)	apple, carrot, cabbage, etc.	dimethoate, profenofos, malathion, etc.	5700	5700	GC–PFPD	(Omeje et al., 2022)
10	2022	The United Arab Emirates (Dubai)	apple, guava, mango, etc.	dimethoate, chlorpyrifos, profenofos, etc.	13,484	13,479	LC–MS/MS GC–MS/MS	(Osaili et al., 2022a)
11	2022	The United Arab Emirates (Dubai)	cucumber, gourd, okra, etc.	chlorpyrifos, dimethoate, profenofos, etc.	24,098	24,098	LC–MS/MS GC–MS/MS	(Osaili et al., 2022b)
12	2016	India (Lucknow)	cabbage, eggplant, banana, etc.	chlorpyrifos, malathion	36	6	GC–MS	(Rai et al., 2016)
13	2014	Thailand (Phayao)	springonion, garlic, onion, etc.	chlorpyrifos, dimethoate, malathion, etc.	162	74	GC–FPD	(Sapbamrer and Hongsibsong, 2014)
14	2015	Kazakhstan (Almaty)	cucumber, tomato	chlorpyrifos-ethyl, chlorpyrifos, triazophos, etc.	115	7	GC–NPD	(Lozowicka et al., 2015)
15	2021	China (Shaanxi)	spinach, cabbage	parathion, fenamiphos, triazophos, etc.	21	21	GC–FPD	(Li et al., 2021)
16	2022	China (Guangxi, Hunan, Hubei, etc.)	orange, kumquat, pummelo, etc.	chlorpyrifos, profenofos, triazophos, etc.	4899	844	LC–MS/MS GC–MS/MS	(Li et al., 2022)
17	2019	Iran (Tehran)	cucumber, tomato	chlorpyrifos, phosalone	45	20	GC–MS	(Hadian et al., 2019)
18	2014	Iran (Kerman)	cucumber	diazinon	60	32	GC–NPD	(Rohani et al., 2014)
19	2013	Ghana (Komenda Edina Eguafo Abrem)	okra	diazinon, chlorpyrifos, phorate, etc.	6500	6500	GC–MS	(Essumang et al., 2013)
20	2023	Turkey (Diyarbakır)	cucumber, tomato, pepper, etc.	chlorpyrifos, malathion	50	8	LC–MS/MS GC–MS/MS	(Elmastas et al., 2023)
21	2020	Chile (Metropolitana)	lettuce, tomato	methamidophos, chlorpyrifos	160	160	GC–NPD	(Elgueta et al., 2020)
22	2020	Trinidad and Tobago (Chaguanas)	pepper, lettuce, tomato	ethion, diazinon	12	3	GC–MS	(Collimore and Bent, 2020)
23	2018	Brazil (Fortaleza)	sapodilla fruit	chlorpyrifos	13	5	GC–MS	(Alcantara et al., 2018)
24	2015	Ghana (Kumasi)	eggplant, okra, tomato	chlorpyrifos, methidathion, diazinon, etc.	320	320	GC–PFPD	(Akoto et al., 2015)

122.48]), followed by samples from China (*M* = 18.31 μg/kg, 95 % CI [12.86, 23.76]). Ghana exhibited the highest chlorpyrifos concentrations (*M* = 306.64 μg/kg, 95 % CI [204.46, 408.05]).

Profenofos was found in samples from seven countries, with an estimated mean of 43.50 μg/kg (95 % CI [41.99, 45.01]). Among these, profenofos was primarily detected in the UAE samples (*M* = 114.81 μg/kg, 95 % CI [89.87, 139.76]), followed by Chinese samples (*M* = 38.09 μg/kg, 95 % CI [13.58, 62.61]). Nigeria showed the highest profenofos concentrations (*M* = 281.64 μg/kg, 95 % CI [262.69, 300.59]).

Dimethoate was found in samples from six countries, with an estimated mean of 22.26 μg/kg (95 % CI [21.29, 23.22]). Among these, dimethoate was detected most often in the UAE samples (*M* = 112.24 μg/kg, 95 % CI [82.54, 141.94]), followed by the Iran samples (*M* = 9.84 μg/kg, 95 % CI [9.76, 9.92]).

Methamidophos was found in five countries' samples with an estimated mean of 42.74 μg/kg (95 % CI [13.25, 72.24]). Among these, methamidophos was primarily detected in the UAE (*M* = 61.83 μg/kg, 95 % CI [50.21, 73.46]), then in the Iran samples (*M* = 9.89 μg/kg, 95 % CI [9.75, 10.02]).

Acephate was found in three countries' samples with an estimated mean of 19.86 μg/kg (95 % CI [18.25, 21.47]). Among these, acephate was primarily detected in the UAE (*M* = 223.04 μg/kg, 95 % CI [169.49, 276.59]), then in the India samples (*M* = 6.68 μg/kg, 95 % CI [5.37, 7.99]).

Triazophos was found in three countries' samples with an estimated mean of 31.53 μg/kg (95 % CI [23.06, 39.65]). Among these, triazophos was mainly found in the UAE (*M* = 174.73 μg/kg, 95 % CI [–11.47, 360.93]), followed by samples from China (*M* = 5.11 μg/kg, 95 % CI [3.31, 6.90]).

Omethoate was found in samples from three countries with an estimated mean of 71.59 μg/kg (95 % CI [65.19, 78.00]). Among these, omethoate was mainly found in the UAE (*M* = 59.02 μg/kg, 95 % CI [48.76, 69.27]), followed by samples from China (*M* = 56.90 μg/kg, 95 % CI [47.36, 66.44]).

Diazinon was found in six countries' samples with an estimated mean of 26.86 μg/kg (95 % CI [21.29, 23.22]). Among these, diazinon was detected most often in the Iran samples (*M* = 2.39 μg/kg, 95 % CI [2.11, 2.67]), followed by Chinese samples (*M* = 42.51 μg/kg, 95 % CI [7.66, 92.69]). Thailand displayed the highest diazinon concentrations (*M* = 79.35 μg/kg, 95 % CI [–42.04, 200.74]).

Fenitrothion was found in five countries' samples with an estimated mean of 6.89 μg/kg (95 % CI [6.57, 7.20]). Among these, fenitrothion

Table 2
Subgroup *meta*-analysis for the mean of estimated OPs levels (μg/kg) by countries (based on top 10 OPs with the highest detection frequency).

OPs	Country	Total sample size	Positive samples (Valid samples)[a]	Mean, 95 % CI (μg/kg)	Hetrogeneity I^2(%)	P from test of Heterogeneity	Model	Reference
Chlorpyrifos	United Arab Emirates	3988	3988 (3362)	99.09, [75.70, 122.48]	98.6	0	Random	(Osaili et al., 2022a) (Osaili et al., 2022b)
	China	1711	518 (516)	18.31, [12.86, 23.76]	99.3	0	Random	(Wang et al., 2013) (Li et al., 2017)
	Iran	1110	1095 (1095)	1.67, [1.55, 1.80]	99.4	0	Random	(Taghizadeh et al., 2021) (Hadian et al., 2019)
	India	686	288 (287)	22.11, [18.00, 26.22]	99.9	0	Random	(Narenderan et al., 2019) (Rai et al., 2016)
	Ghana	592	584 (584)	306.64, [204.46, 408.05]	99.9	0	Random	(Okoffo et al., 2016) (Essumang et al., 2013) (Akoto et al., 2015)
	Thailand	65	32 (28)	17.61, [9.59, 25.63]	51	0.031	Random	(Sapbamrer and Hongsibsong, 2014)
	Chile	80	80 (57)	N.C.[b]	N.C.	N.C.	N.C.	(Elgueta et al., 2020)
	Turkey	40	7 (5)	N.C.	N.C.	N.C.	N.C.	(Elmastas et al., 2023)
	Kazakhstan	19	1 (0)	N.C.	N.C.	N.C.	N.C.	(Lozowicka et al., 2015)
	Brazil	13	5(4)	N.C.	N.C.	N.C.	N.C.	(Alcantara et al., 2018)
	Total	8304	6598 (5938)	14.43, [14.00, 14.85]	99.9	0	Random	The above 16 studies
Profenofos	United Arab Emirates	4331	4331 (2619)	114.81, [89.87, 139.76]	98.1	0	Random	(Osaili et al., 2022a) (Osaili et al., 2022b)
	China	1633	252 (252)	38.09, [13.58, 62.61]	87.3	0	Random	(Mao et al., 2021)
	India	659	283 (277)	6.10, [4.70, 7.50]	99.9	0	Random	(Narenderan et al., 2019)
	Ghana	520	520 (520)	9.88, [1.37, 18.45]	89.1	0.002	Random	(Essumang et al., 2013) (Akoto et al., 2015)
	Nigeria	300	300 (240)	281.64, [262.69, 300.59]	95.9	0	Random	(Omeje et al., 2022)
	Ethiopia	50	5 (5)	N.C.	N.C.	N.C.	N.C.	(Wondimu al., 2023)
	Thailand	13	2 (0)	N.C.	N.C.	N.C.	N.C.	(Sapbamrer and Hongsibsong, 2014)
	Total	7506	5693 (3913)	43.50, [41.99, 45.01]	100	0	Random	The above 9 studies
Dimethoate	United Arab Emirates	4319	4319 (2930)	112.24, [82.54, 141.94]	99	0	Random	(Osaili et al., 2022a) (Osaili et al., 2022b)
	Iran	1080	1080 (1080)	9.84, [9.76, 9.92]	79.4	0	Random	(Taghizadeh et al., 2021)
	Ghana	540	540 (540)	57.98, [16.27, 99.69]	99.9	0	Random	(Essumang et al., 2013) (Akoto et al., 2015)
	Nigeria	300	300 (180)	84.44, [82.76, 86.13]	99.4	0	Random	(Omeje et al., 2022)
	China	209	71 (71)	73.47, [50.35, 96.59]	99.9	0	Random	(Wang et al., 2013) (Yu et al., 2016)
	Kazakhstan	19	2 (2)	N.C.	N.C.	N.C.	N.C.	(Lozowicka et al., 2015)
	Total	6467	6312 (4803)	22.26, [21.29, 23.22]	99.8	0	Random	The above 9 studies
Methamidophos	United Arab Emirates	4207	4207 (2621)	61.83, [50.21, 73.46]	96.6	0	Random	(Osaili et al., 2022a) (Osaili et al., 2022b)
	Iran	1080	1080 (1080)	9.89, [9.75, 10.02]	51.67	0.019	Random	(Taghizadeh et al., 2021)
	Ghana	560	560 (560)	11.50, [6.35, 16.66]	99.7	0	Random	(Essumang et al., 2013) (Akoto et al., 2015)
	China	178	37 (36)	94.60, [−59.71, 248.91]	100	0	Random	(Yu et al., 2016)
	Chile	80	80 (80)	947.08, [−814.36, 2708.51]	84.19	0.012	Random	(Elgueta et al., 2020)
	Total	6105	5964 (4377)	42.74, [13.25, 72.24]	100	0	Random	The above 7 studies
Acephate	United Arab Emirates	5502	5502 (3540)	223.04, [169.49, 276.59]	99.2	0	Random	(Osaili et al., 2022a) (Osaili et al., 2022b)
	India	659	283 (277)	6.68, [5.37, 7.99]	99.9	0	Random	(Narenderan et al., 2019)
	China	76	3 (2)	N.C.	N.C.	N.C.	N.C.	(Wang et al., 2013)
	Total	6237	5788 (3819)	19.86, [18.25, 21.47]	99.2	0	Random	The above 4 studies
Triazophos	United Arab Emirates	3672	3672 (1058)	174.73, [−11.47, 360.93]	99.3	0	Random	(Osaili et al., 2022a) (Osaili et al., 2022b)

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Table 2 (*continued*)

OPs	Country	Total sample size	Positive samples (Valid samples)[a]	Mean, 95 % CI (μg/kg)	Hetrogeneity I^2(%)	P from test of Heterogeneity	Model	Reference
	China	1716	89 (87)	5.11, [3.31, 6.90]	51.7	0.035	Random	(Zhao et al., 2015) (Li et al., 2021) (Li et al., 2022)
	Kazakhstan	29	1 (0)	N.C.	N.C.	N.C.	N.C.	(Lozowicka et al., 2015)
	Total	5417	3762 (1145)	31.53, [23.06, 39.65]	98	0	Random	The above 6 studies
Omethoate	United Arab Emirates	4610	4610 (3739)	59.02, [48.76, 69.27]	98.6	0	Random	(Osaili et al., 2022a) (Osaili et al., 2022b)
	China	224	57 (55)	56.90, [47.36, 66.44]	100	0	Random	(Wang et al., 2013) (Yu et al., 2016)
	Thailand	3	3 (3)	N.C.	N.C.	N.C.	N.C.	(Sapbamrer and Hongsibsong, 2014)
	Total	4837	4670 (3797)	71.59, [65.19, 78.00]	99.9	0	Random	The above 5 studies
Diazinon	Iran	1140	1112 (1112)	2.39, [2.11, 2.67]	99.9	0	Random	(Taghizadeh et al., 2021) (Rohani et al., 2014)
	China	254	178 (178)	42.51, [7.66, 92.69]	100	0	Random	(Yu et al., 2016) (Zhao et al., 2015)
	Thailand	25	16 (15)	79.35, [−42.04, 200.74]	99.9	0	Random	(Sapbamrer and Hongsibsong, 2014)
	United Arab Emirates	666	666 (0)	N.C.	N.C.	N.C.	N.C.	(Osaili et al., 2022a) (Osaili et al., 2022b)
	Ghana	532	518 (500)	N.C.	N.C.	N.C.	N.C.	(Okoffo et al., 2016) (Essumang et al., 2013)
	Trinidad and Tobago	6	1 (0)	N.C.	N.C.	N.C.	N.C.	(Collimore and Bent, 2020)
	Total	2623	2491 (1805)	26.86, [23.69, 30.03]	100	0	Random	The above 10 studies
Fenitrothion	Iran	1080	1080 (1080)	1.42, [1.27, 1.56]	99.8	0	Random	(Taghizadeh et al., 2021)
	Nigeria	300	300 (180)	100.00, [98.54, 101.46]	0	1	Fixed	(Omeje et al., 2022)
	China	178	45 (43)	6.83, [0.53, 13.12]	99.9	0	Random	(Yu et al., 2016)
	Ghana	500	500 (500)	N.C.	N.C.	N.C.	N.C.	(Essumang et al., 2013)
	Thailand	3	1 (0)	N.C.	N.C.	N.C.	N.C.	(Sapbamrer and Hongsibsong, 2014)
	Total	2061	1926 (1803)	6.89, [6.57, 7.20]	99.9	0	Random	The above 5 studies
Phorate	Ghana	540	540 (540)	10.13, [4.75, 25.01]	99.8	0	Random	(Essumang et al., 2013) (Akoto et al., 2015)
	China	254	104 (104)	41.48, [33.33, 49.63]	100	0	Random	(Wang et al., 2013) (Yu et al., 2016)
	United Arab Emirates	748	748 (0)	N.C.	N.C.	N.C.	N.C.	(Osaili et al., 2022a) (Osaili et al., 2022b) (Essumang et al., 2013)
	Nigeria	300	300 (0)	N.C.	N.C.	N.C.	N.C.	(Omeje et al., 2022)
	Total	1842	1692 (644)	32.62, [25.73, 39.51]	100	0	Random	The above 8 studies

[a] Due to the reporting of a standard deviation of 0.00 for certain positive samples in some of the studies, which makes the *meta*-analysis of these samples becomes unfeasible. Therefore, the number of samples employed in the *meta*-analysis is designated as “valid samples”.

[b] Due to the insufficient number of non-zero standard deviations (SDs) in specific subgroups, it was not possible to perform a *meta*-analysis. Consequently, these subgroups were represented by the abbreviation “N.C.” to indicate the inability to calculate.

was found most often in Iran samples (*M* = 1.42 μg/kg, 95 % CI [1.27, 1.56]). Nigeria exhibited the highest fenitrothion concentrations (*M* = 100.00 μg/kg, 95 % CI [98.54, 101.46]).

Lastly, phorate was detected in samples from four countries (*M* = 32.62 μg/kg, 95 % CI [25.73, 39.51]). Among these, phorate was detected most often in samples from Ghana (M = 10.13 μg/kg, 95 % CI [4.75, 25.01]), followed by Chinese samples (*M* = 41.48 μg/kg, 95 % CI [33.33, 49.63]).

3.4. *Estimated mean concentration of OPs in different types of fruits and vegetables*

Chlorpyrifos was detected in the largest number of fruit samples (*M* = 3.34 μg/kg, 95 % CI [3.11, 3.56]), followed by fruit vegetable samples (*M* = 123.05 μg/kg, 95 % CI [101.19, 144.91]).

Profenofos was found in the largest number of fruit vegetable samples (*M* = 60.57 μg/kg, 95 % CI [55.25, 65.89]), followed by fruit samples (*M* = 32.48 μg/kg, 95 % CI [28.81, 36.15]). It is worth noting that beans showed the highest concentrations of profenofos (*M* = 92.71 μg/kg, 95 % CI [59.29, 126.13]).

Dimethoate was detected in the largest number of fruit vegetable samples (*M* = 65.65 μg/kg, 95 % CI [56.95, 74.34]), followed by fruit samples (*M* = 10.29 μg/kg, 95 % CI [9.95, 10.63]). In addition, beans presented the highest concentrations of dimethoate (*M* = 94.26 μg/kg, 95 % CI [6.07, 182.45]).

Methamidophos was found in the highest quantity of fruit vegetable samples (*M* = 31.46 μg/kg, 95 % CI [23.87, 39.06]), followed by fruit samples (*M* = 20.24 μg/kg, 95 % CI [17.19, 23.30]). Notably, the leafy vegetables showed the highest concentration of methamidophos (*M* = 299.48 μg/kg, 95 % CI [−55.92, 654.88]). The large standard deviations influence the 95 % CI, including zero in some samples.

Acephate was most frequently found in fruit vegetable samples (*M* =

103.00 μg/kg, 95 % CI [92.14, 113.85]), followed by fruit samples ($M = 62.32$ μg/kg, 95 % CI [46.20, 78.44]).

Triazophos was detected in the highest quantity of fruit samples ($M = 5.84$ μg/kg, 95 % CI [4.48, 7.19]). The insufficient non-zero standard deviations in other subgroups limited us from performing a *meta*-analysis. Consequently, these subgroups were represented by the abbreviation "N.C." (short for non-calculate) in Table 3.

Omethoate appeared most often in fruit vegetable samples ($M = 70.36$ μg/kg, 95 % CI [60.72, 80.01]), followed by fruit samples ($M = 60.85$ μg/kg, 95 % CI [46.78, 74.93]). Notably, beans exhibited the highest pollution level of omethoate ($M = 94.26$ μg/kg, 95 % CI [6.07, 182.45]).

Diazinon was primarily found in fruit samples ($M = 2.38$ μg/kg, 95 % CI [2.11, 2.66]), followed by fruit vegetable samples ($M = 30.73$ μg/kg, 95 % CI [15.02, 46.44]). Notably, the leafy vegetables displayed the highest diazinon concentration at 124.91 μg/kg with a 95 % CI [16.91, 232.92].

Fenitrothion was primarily detected in fruit samples ($M = 1.42$ μg/kg, 95 % CI [1.27, 1.56]), then in fruit vegetable samples ($M = 51.25$ μg/kg, 95 % CI [9.99, 92.51]). Notably, root vegetables showed the highest concentration at 54.59 μg/kg, 95 % CI [– 43.27, 146.45].

Lastly, phorate was primarily detected in fruit vegetable samples ($M = 6.66$ μg/kg, 95 % CI [3.23, 10.09]), then in root vegetable samples ($M = 292.25$ μg/kg, 95 % CI [–262.03, 846.53]). Notably, root vegetables showed the highest concentration at 54.59 μg/kg, 95 % CI [– 43.27, 146.45].

4. Discussion

The short growth cycles and limited shelf lives of fruits and vegetables make them particularly prone to containing OP residues. Our *meta*-analysis findings indicated that while the concentrations of residual OPs in most fruits and vegetables conformed to international or national safety standards, the concentrations exceeded MRLs in a small number of samples, which posed certain safety risks.

At a national level, methamidophos, acephate, diazinon, fenitrothion, and phorate were detected in all fruit and vegetable samples. The concentrations of these substances detected in the samples complied with the MRLs set by the CAC and EU international organisations (Table 2 and Table S6).

However, the estimated residual concentrations of omethoate in fruit and vegetable samples from China and the UAE exceeded the MRLs (10–50 μg/kg) set by the CAC, the EU, and China. This raises concerns that OP residues may persist in fruit and vegetables in China, despite pesticide usage in China having declined substantially, i.e., in 2020, it was ranked third in the world for pesticide usage, which was a lower ranking than in previous years. Moreover, it is concerning that the residual concentrations of dimethoate in samples from the UAE, Ghana, Nigeria, and China all surpassed the MRLs established by the EU and the UK (10–50 μg/kg), with only Iran meeting the EU standard. Additionally, fruit and vegetable samples from the UAE and Nigeria contained residual concentrations of profenofos that exceeded the MRLs set by the UK, and residual concentrations of triazophos that exceeded the MRLs set by the EU and the UK. Furthermore, fruit and vegetable samples from the UAE, China, India, Ghana, and Thailand contained residual concentrations of chlorpyrifos that exceeded the maximum allowed dose, with Ghana's samples exhibiting alarmingly high residual concentrations of chlorpyrifos, reaching 306.64 μg/kg, 30 times higher than the EU and UK's standards.

As the EU ranks first globally in terms of OP utilisation, accounting for up to 45 % of their usage, we explore the EU regulations on MRLs of different OPs in fruits and vegetables. Based on these regulations, we further investigate the residual concentrations of various OPs, categorised by fruit and vegetable type (Table S3).

The analyses in Table 3 and Table S7 reveal that out of the 10 OP residue analyses conducted on samples of five types of fruits and vegetables, 16 groups of concentrations exceeded the safety standard set by the EU. This amounts to approximately 32 % (16/50) of the samples. Specifically, in fruits and fruit vegetables, only two OPs exceeded the MRL criterion of the EU, namely acephate and omethoate in fruits, and chlorpyrifos and dimethoate in fruit vegetables. In samples of leafy vegetables, the residual concentrations of four OPs exceeded the MRL criterion of the EU, namely those of chlorpyrifos, methamidophos, acephate, and omethoate. Similarly, in samples of root vegetables, the residual concentrations of four OPs surpassed the EU safety standards, namely those of chlorpyrifos, profenofos, fenitrothion, and phorate. In beans, the residual concentrations of four OPs exceeded MRL criterion of the EU, namely those of chlorpyrifos, profenofos, dimethoate, and omethoate. The residual concentrations of chlorpyrifos were also alarmingly high in fruit vegetables, reaching 123.05 μg/kg, which is over 12 times the safety standard. Additionally, the residual concentrations of phorate in root vegetables were as high as 292.25 μg/kg, nearly 15 times the safety standard.

The diverse dietary structures, agricultural product types, climates, soil conditions, and levels of development across countries account for substantial variations in the MRL standards for OPs in fruits and vegetables, as mandated by different governments and international organisations. The rapid growth of agricultural trade has further complicated the effective control of pesticide residues worldwide. Therefore, it is crucial to promote the refinement and standardisation of pesticide residue regulations, strengthen pesticide residue analysis, accelerate the development and adoption of environmentally friendly pesticides, and advocate for judicious pesticide use. This is because such measures are effective in addressing the issue of excessive pesticide residues.

It is essential to acknowledge that this study has several limitations, as detailed below. These limitations also indicate potential directions for future research:

1. The influence of factors such as the cleaning and peeling of fruits and vegetables, which is essential for guiding residents in appropriate pre-consumption treatment, was not thoroughly examined due to the limited number of studies available. In-depth exploration of these factors is warranted in future research.
2. As most of the test methods that have been used in the literature are chromatography-based methods, such as gas chromatography and liquid chromatography methods, it is crucial to consider various factors, including the expertise of operators, sample pretreatment methods, and equipment used, as they might have influenced the final test results and introduced biases into the *meta*-analysis.
3. Variations in the number of studies and samples included across different countries, together with considerable differences between studies' sample sizes, should be considered when interpreting our findings.
4. This *meta*-analysis was based on published articles, which may only partially represent the overall occurrence of OPs in fruit and vegetable samples at a national level. Therefore, future studies could also include articles published by FDA-equivalent organisations of various countries to increase the sample size for *meta*-analyses.
5. This study focused on research conducted after 2013, when the FAO adopted the International Code of Conduct on Pesticide Management, which might have affected the comprehensiveness of the study findings. Therefore, future research should analyse all relevant literature to cross-validate the conclusions drawn from this study.

5. Conclusion

The *meta*-analysis conducted in this study represents the first comprehensive examination of residual concentrations of various OPs in fresh fruits and vegetables following the adoption of The International Code of Conduct on Pesticide Management (2013–2023). The study primarily relied on detection data from published literature as samples. The resulting diverse dataset incorporated sample information from

Table 3

Subgroup *meta*-analysis for the mean of estimated OPs levels (μg/kg) by fruit and vegetable species (based on top 10 OPs with the highest detection frequency).

OPs	Fruits and vegetables species	Total sample size	Positive samples (Valid samples)[a]	Mean, 95 % CI (μg/kg)	Hetrogeneity I^2(%)	P from test of Heterogeneity	Model	Reference
Chlorpyrifos	Fruits	4971	3587 (3150)	3.34, [3.11, 3.56]	99.6	0	Random	(Taghizadeh et al., 2021) (Narenderan et al., 2019) (Osaili et al., 2022a) (Rai et al., 2016) (Li et al., 2022) (Alcantara et al., 2018)
	Fruit vegetables	2231	2142 (2115)	123.05, [101.19, 144.91]	99.9	0	Random	(Narenderan et al., 2019) (Osaili et al., 2022b) (Sapbamrer and Hongsibsong, 2014) (Lozowicka et al., 2015) (Elmastas et al., 2023) (Hadian et al., 2019) (Akoto et al., 2015) (Elgueta et al., 2020) (Essumang et al., 2013)
	Beans	461	377 (376)	19.98, [15.37, 24.60]	98.6	0	Random	(Wang et al., 2013) (Narenderan et al., 2019) (Okoffo et al., 2016) (Osaili et al., 2022b) (Sapbamrer and Hongsibsong, 2014)
Chlorpyrifos	Leafy vegetables	445	337 (142)	20.78, [16.59, 24.97]	99.7	0	Random	(Wang et al., 2013) (Narenderan et al., 2019) (Osaili et al., 2022b) (Rai et al., 2016) (Sapbamrer and Hongsibsong, 2014) (Elgueta et al., 2020)
	Root vegetables	196	155 (155)	27.82, [13.23, 42.41]	99.9	0	Random	(Narenderan et al., 2019) (Sapbamrer and Hongsibsong, 2014)
	Total	8304	6598 (5938)	14.43, [14.00, 14.85]	99.9	0	Random	The above 16 studies
Profenofos	Fruit vegetables	3174	3106 (2580)	60.57, [55.25, 65.89]	100	0	Random	(Wondimu al., 2023) (Omeje et al., 2022) (Osaili et al., 2022b) (Sapbamrer and Hongsibsong, 2014) (Essumang et al., 2013) (Akoto et al., 2015) (Narenderan et al., 2019)
	Fruits	2786	1169 (688)	32.48, [28.81, 36.15]	99.7	0	Random	(Omeje et al., 2022) (Osaili et al., 2022a) (Mao et al., 2021) (Narenderan et al., 2019)
	Beans	610	550 (146)	92.71, [59.29, 126.13]	100	0	Random	(Omeje et al., 2022) (Osaili et al., 2022b) (Narenderan et al., 2019)
	Root vegetables	512	477 (202)	70.74, [60.67, 80.82]	100	0	Random	(Omeje et al., 2022) (Osaili et al., 2022b) (Narenderan et al., 2019)
Profenofos	Leafy vegetables	424	391 (297)	8.84, [6.30, 11.38]	99.4	0	Random	(Omeje et al., 2022) (Osaili et al., 2022b) (Sapbamrer and Hongsibsong, 2014) (Narenderan et al., 2019)
	Total	7506	5693 (3913)	43.50, [41.99, 45.01]	100	0	Random	The above 9 studies

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Table 3 (*continued*)

OPs	Fruits and vegetables species	Total sample size	Positive samples (Valid samples)[a]	Mean, 95 % CI (μg/kg)	Hetrogeneity I^2(%)	P from test of Heterogeneity	Model	Reference
Dimethoate	Fruit vegetables	3486	3380 (2697)	65.65, [56.95, 74.34]	99.9	0	Random	(Wang et al., 2013) (Yu et al., 2016) (Omeje et al., 2022) (Osaili et al., 2022b) (Lozowicka et al., 2015) (Essumang et al., 2013) (Akoto et al., 2015)
	Fruits	2120	2120 (1609)	10.29, [9.95, 10.63]	98.6	0	Random	(Omeje et al., 2022) (Osaili et al., 2022a) (Taghizadeh et al., 2021)
	Beans	525	525 (386)	94.26, [6.07, 182.45]	99.3	0	Random	(Omeje et al., 2022) (Osaili et al., 2022b)
	Leafy vegetables	260	219 (103)	28.42, [18.84, 38.00]	100	0	Random	(Yu et al., 2016) (Omeje et al., 2022) (Osaili et al., 2022b) (Wang et al., 2013)
	Root vegetables	76	68 (8)	N.C.[b]	N.C.	N.C.	N.C.	(Yu et al., 2016) (Omeje et al., 2022)
	Total	6467	6312 (4803)	22.26, [21.29, 23.22]	99.8	0	Random	The above 9 studies
Methamidophos	Fruit vegetables	3392	3306 (2550)	31.46, [23.87, 39.06]	99.9	0	Random	(Yu et al., 2016) (Osaili et al., 2022b) (Elgueta et al., 2020) (Essumang et al., 2013) (Akoto et al., 2015)
	Fruits	2188	2188 (1741)	20.24, [17.19, 23.30]	99.9	0	Random	(Osaili et al., 2022a) (Taghizadeh et al., 2021)
	Leafy vegetables	355	310 (80)	299.48, [−55.92, 654.88]	100	0	Random	(Yu et al., 2016) (Osaili et al., 2022b) (Elgueta et al., 2020)
	Root vegetables	170	160 (6)	N.C.	N.C.	N.C.	N.C.	(Yu et al., 2016) (Osaili et al., 2022b)
	Beans	0	0 (0)	N.C.	N.C.	N.C.	N.C.	–
	Total	6105	5964 (4377)	42.74, [13.25, 72.24]	100	0	Random	The above 7 studies
Acephate	Fruit vegetables	2873	2854 (2452)	103.00, [92.14, 113.85]	99.6	0	Random	(Osaili et al., 2022b) (Narenderan et al., 2019)
	Fruits	2645	2409 (995)	62.32, [46.20, 78.44]	99.9	0	Random	(Osaili et al., 2022a) (Narenderan et al., 2019)
	Root vegetables	397	303 (287)	6.42, [4.95, 7.88]	99.6	0	Random	(Osaili et al., 2022b) (Wang et al., 2013) (Narenderan et al., 2019)
	Leafy vegetables	237	197 (60)	23.51, [19.45, 27.57]	99.9	0	Random	(Wang et al., 2013) (Osaili et al., 2022b) (Narenderan et al., 2019)
	Beans	85	25 (25)	3.95, [3.72, 4.17]	53.6	0	Random	(Narenderan et al., 2019)
	Total	6237	5788 (3819)	19.86, [18.25, 21.47]	99.2	0	Random	The above 4 studies
Triazophos	Fruits	2248	699 (84)	5.84, [4.48, 7.19]	0	0.623	Fixed	(Osaili et al., 2022a) (Mao et al., 2021)
	Fruit vegetables	2966	2860 (919)	N.C.	N.C.	N.C.	N.C.	(Zhao et al., 2015) (Osaili et al., 2022b) (Lozowicka et al., 2015)
	Root vegetables	139	139 (139)	N.C.	N.C.	N.C.	N.C.	(Osaili et al., 2022b)
	Beans	61	61 (0)	N.C.	N.C.	N.C.	N.C.	(Osaili et al., 2022b)
	Leafy vegetables	3	3 (3)	N.C.	N.C.	N.C.	N.C.	(Li et al., 2021)
	Total	5417	3762 (1145)	31.53, [23.06, 39.65]	98	0	Random	The above 6 studies
Omethoate	Fruit vegetables	2612	2517 (2312)	70.36, [60.72, 80.01]	99.8	0	Random	(Wang et al., 2013) (Yu et al., 2016) (Osaili et al., 2022b)
	Fruits	1721	1721 (1055)	60.85, [46.78, 74.93]	99.3	0	Random	(Osaili et al., 2022a)

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Table 3 (*continued*)

OPs	Fruits and vegetables species	Total sample size	Positive samples (Valid samples)[a]	Mean, 95 % CI (μg/kg)	Hetrogeneity I^2(%)	P from test of Heterogeneity	Model	Reference
	Beans	386	386 (386)	94.26, [6.07, 182.45]	97.6	0	Random	(Osaili et al., 2022b)
	Leafy vegetables	102	39 (37)	113.20, [88.91, 137.50]	100	0	Random	(Wang et al., 2013) (Yu et al., 2016) (Sapbamrer and Hongsibsong, 2014)
	Root vegetables	16	7 (7)	N.C.	N.C.	N.C.	N.C.	(Yu et al., 2016)
	Total	4837	4670 (3797)	71.59, [65.19, 78.00]	99.9	0	Random	The above 5 studies
Diazinon	Fruits	1317	1317 (1080)	2.38, [2.11, 2.66]	99.9	0	N.C.	(Taghizadeh et al., 2021) (Osaili et al., 2022a)
	Fruit vegetables	736	638 (637)	30.73, [15.02, 46.44]	100	0	Random	(Yu et al., 2016) (Zhao et al., 2015) (Rohani et al., 2014) (Essumang et al., 2013)
	Leafy vegetables	192	175 (70)	124.91, [16.91, 232.92]	100	0	Random	(Yu et al., 2016) (Osaili et al., 2022b) (Sapbamrer and Hongsibsong, 2014)
	Root vegetables	21	18 (18)	26.19, [−10.76, 63.14]	99.8	0	Random	(Yu et al., 2016) (Sapbamrer and Hongsibsong, 2014)
	Beans	357	343 (0)	N.C.	N.C.	N.C.	N.C.	(Okoffo et al., 2016) (Osaili et al., 2022b)
	Total	2623	2491 (1805)	26.86, [23.69, 30.03]	100	0	Random	The above 9 studies
Fenitrothion	Fruits	1140	1140 (1080)	1.42, [1.27, 1.56]	99.8	0	Random	(Taghizadeh et al., 2021) (Omeje et al., 2022)
	Fruit vegetables	654	568 (566)	51.25, [9.99, 92.51]	100	0	Random	(Yu et al., 2016) (Omeje et al., 2022) (Essumang et al., 2013)
	Leafy vegetables	128	93 (93)	35.51, [13.96, 57.05]	100	0	Random	(Yu et al., 2016) (Omeje et al., 2022)
	Root vegetables	79	65 (64)	54.59, [−43.27, 146.45]	100	0	Random	(Yu et al., 2016) (Omeje et al., 2022) (Sapbamrer and Hongsibsong, 2014)
	Beans	60	60 (0)	N.C.	N.C.	N.C.	N.C.	(Omeje et al., 2022)
	Total	2061	1926 (1803)	6.89, [6.57, 7.20]	99.9	0	Random	The above 5 studies
Phorate	Fruit vegetables	694	644 (584)	6.66, [3.23, 10.09]	99.9	0	Random	(Yu et al., 2016) (Omeje et al., 2022) (Essumang et al., 2013) (Akoto et al., 2015)
	Root vegetables	296	229 (9)	292.25, [−262.03, 846.53]	99.9	0	Random	(Wang et al., 2013) (Yu et al., 2016) (Omeje et al., 2022) (Osaili et al., 2022b)
	Leafy vegetables	144	111 (51)	12.40, [−3.02, 27.82]	100	0	Random	(Wang et al., 2013) (Yu et al., 2016) (Omeje et al., 2022)
	Fruits	648	648 (0)	N.C.	N.C.	N.C.	N.C.	(Omeje et al., 2022) (Osaili et al., 2022a)
	Beans	60	60 (0)	N.C.	N.C.	N.C.	N.C.	(Omeje et al., 2022)
	Total	1842	1692 (644)	32.62, [25.73, 39.51]	100	0	Random	The above 7 studies

[a] Due to the reporting of a standard deviation of 0.00 for certain positive samples in some of the studies, which makes the *meta*-analysis of these samples becomes unfeasible. Therefore, the number of samples employed in the *meta*-analysis is designated as “valid samples”.

[b] Due to the insufficient number of non-zero standard deviations (SDs) in specific subgroups, it was not possible to perform a *meta*-analysis. Consequently, these subgroups were represented by the abbreviation “N.C.” to indicate the inability to calculate.

different countries, facilitating a multifaceted assessment of OP residues and pollution concentrations.

Our findings reveal that the residual concentrations of the top-10 most commonly detected OPs (e.g., chlorpyrifos, profenofos, and dimethoate) in fruit and vegetable samples from most countries complied with international standards set by organisations such as CAC, the EU, and the national standards of the UK and China. However, samples from a few countries, such as Ghana and the UAE, had residual concentrations of OPs that exceeded the above-mentioned standards. Moreover, approximately 32 % of the samples of different types of fruits and vegetables contained excessive residual concentrations of OPs. In particular, four types of fruit and vegetables exhibited residual concentrations of chlorpyrifos exceeding the EU safety standard, with fruit vegetables having the highest residual concentration (which surpassed the standard by 12 times). The aforementioned results highlight the risk that unsafe residual concentrations of commonly used OPs (e.g., chlorpyrifos) are present in fruit and vegetables.

Future optimisations will be conducted to address the limitations and gaps in this study, such as by using a larger sample size in future work. Ultimately, this study will support more comprehensive investigations of residual concentrations of OP residues in fruits and vegetables, which will guide efforts to mitigate food safety hazards caused by these residues.

CRediT authorship contribution statement

Wenjun Li: Conceptualization, Methodology, Project administration, Resources, Writing – review & editing. **Junlong Chen:** Data curation, Formal analysis, Investigation. **Fangzhou Linli:** Data curation, Investigation. **Xianggui Chen:** Funding acquisition, Project administration, Resources. **Yukun Huang:** Funding acquisition, Methodology. **Xiao Yang:** Resources, Formal analysis.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2023.101014.

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