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A comparative study of multi-residue analysis of pesticides in tomato fruits from different cultivation geographical regions in Egypt

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ABSTRACT

This study presents a comprehensive analysis of pesticide residues in tomato fruits from three major agricultural governorates in Egypt: Al-Hadrah (Alexandria), Rosetta (El-Beheira), and Fuwwah (Kafr El Sheikh). Utilizing Gas Chromatography-Mass Spectrometry (GC-MS), the analysis revealed a concerning prevalence of pesticide contamination across all regions. Different pesticide compounds were identified, encompassing organophosphates, pyrethroids, organochlorines, carbamates, triazoles, and other chemical classes. The results indicate significant regional variation in pesticide profiles. Al-Hadrah samples were dominated by organophosphates like chlorpyrifos (16.53% relative abundance), Rosetta showed a high fungicide load led by carboxin (12.46%), and Fuwwah exhibited an alarming profile composed entirely of pesticide residues, heavily dominated by organophosphates such as ethion (19.02%). A critical cross-regional finding was the ubiquitous presence and high relative abundance of organophosphate insecticides, raising major public health concerns due to their acute neurotoxicity. The study also detected several banned or highly hazardous pesticides, including parathion-ethyl (in all regions) and the persistent organic pollutant endosulfan (in Rosetta and Fuwwah), indicating potential regulatory non-compliance and the use of obsolete stocks. The routine detection of complex pesticide "cocktails," along with the use of synergists like piperonyl butoxide, underscores the potential for cumulative and synergistic toxicological effects. These findings highlight widespread and intensive agrochemical application practices, posing significant food safety risks and potential health threats to consumers. The study underscores the urgent need for enhanced regulatory enforcement, monitoring, and the promotion of sustainable integrated pest management strategies in Egyptian tomato cultivation.

Keywords: Pesticide residues; GC-MS; Tomato fruit; QuEChERS method.

INTRODUCTION

The tomato (*Solanum lycopersicum* L.) is one of the most extensively cultivated and consumed vegetable crops globally, prized for its nutritional value and economic importance (León-García et al., 2017). In Egypt, it represents a cornerstone of agricultural production, serving as a vital source of income for farmers and a key component of the national diet (AbdAllah et al., 2024; Hassan and Ahmed, 2018; Siam and Abdelhakim, 2018). To meet the high demands of local and international markets, Egyptian farmers often rely on intensive agricultural practices, which include the widespread application of pesticides to control a broad spectrum of a broad spectrum of pests and diseases, such as *Tuta absoluta*, whiteflies, thrips, and fungal pathogens, that threaten yield and quality (Atia et al., 2024; Moussa et al., 2013).

While the use of these agrochemicals is crucial for securing harvests, their non-judicious application raises significant public health and environmental concerns (Anwar, 2003; Mishra et al., 2021). Pesticide residues can persist on and within harvested produce, potentially leading to human exposure through the diet. Chronic intake of these residues, even at low concentrations, has been associated with a range of adverse health effects, including carcinogenicity, endocrine disruption, and neurological disorders (Mansour, 2008). Consequently, monitoring pesticide residues in food commodities is imperative to ensure food safety and protect consumer health. This has led to the establishment of stringent Maximum Residue Limits (MRLs) by international regulatory bodies, such as the Codex Alimentarius, and national authorities, which define the highest legally tolerable levels of pesticide residues in food and feed (CodexAlimentarius, 2012; Fortin, 2023).

The residue profile of a crop is not static but is influenced by a complex interplay of factors, including the type and application regime of the pesticide, the time between the last application and harvest (pre-harvest interval), and crucially, the environmental conditions of the cultivation area (Fantke and Juraske, 2013). In Egypt, tomato cultivation is spread across diverse geographical regions, from the fertile lands of the Nile Delta to newly reclaimed desert areas. These regions exhibit substantial variations in climate, such as temperature, humidity, and solar radiation, as well as soil type and irrigation practices. These differential agronomic and climatic conditions can significantly affect the dissipation kinetics and final residue levels of pesticides in crops, leading to potential variations in the residue burden of tomatoes from different growing regions (Abdelfatah et al., 2020; Ibrahim and Shalaby, 2023).

Despite the prominence of tomato cultivation in Egypt, comparative studies investigating the geographical variation of multi-pesticide residues are limited. Most existing research focuses on monitoring residues in a single location or market, without systematically linking the findings to the specific cultivation conditions of different geographic zones. Therefore, a comprehensive comparative assessment is necessary to understand how regional cultivation practices and environments influence pesticide residue levels.

This study undertakes a comparative, multi-residue analysis of pesticides in tomato fruits collected from distinct cultivation regions across Egypt, including Alexandria, El-Beheira, and Kafr El Sheikh Governorates. Utilizing validated QuEChERS-based extraction method followed by GC-MS/MS analysis, this study aims to characterize the occurrence of a wide spectrum of pesticide residues in tomatoes and compare their profiles across distinct agroecological zones and cultivation systems in Egypt. The findings from this investigation will provide valuable data for risk assessment, inform regulatory decisions, and support the development of targeted good agricultural practices (GAPs) to enhance the safety of Egyptian tomatoes.

MATERIALS AND METHODS

Sample collection

Tomato fruit samples (*Solanum lycopersicum* L.) were collected at the commercial ripening stage from open-field cultivation systems across three major geographical regions in Egypt, including Alexandria, El-Beheira, and Kafr El Sheikh Governorates. A total of 12 samples (4 from each region) were obtained directly from farms during the primary harvesting season (April 2023). Sampling followed a randomized strategy, where fruits were harvested from multiple plants across different parts of each farm to ensure a representative sample. All samples were immediately placed in sterile polyethylene bags, stored in ice-cooled boxes, and transported to the laboratory. Upon arrival, each sample was homogenized using a commercial food blender, and the resulting homogenate was stored at -20°C until analysis.

Chemicals and reagents

Pesticide analytical standards (≥98% purity) for 35 compounds, including organophosphates, carbamates, pyrethroids, and neonicotinoids, were purchased from Dr. Ehrenstorfer GmbH (Augsburg, Germany). HPLC-grade acetonitrile, methanol and water were purchased from Merck (Darmstadt, Germany). Polyvinylidene fluoride (PVDF) syringe filter (0.2 µm) (Puradisc, Whatman, USA). Primary secondary amine (PSA, bonded silica, 40 µm) was obtained from Supelco, Sigma-Aldrich Co. (USA). Anhydrous magnesium sulfate, sodium chloride, sodium acetate and activated charcoal were purchased from El-Nasr Pharmaceutical Chemicals Co. (El Gomhoriya St., Abu Zaabal Area 491, Qalyub, Egypt) and used without further purification. Stock standard solutions of individual pesticides (1000 µg/mL) were prepared in acetonitrile and stored at -20°C. Working standard mixtures were prepared by appropriate dilution of the stock solutions in acetonitrile on the day of use.

Sample extraction and clean-up

The extraction and clean-up of tomato samples were performed using a modified QuEChERS (Quick, Easy, Cheap, Effective, Rugged, and Safe) method (Anastassiades et al., 2007; Payá et al., 2007). Briefly, a 2 g portion of homogenized tomato sample was weighed into a 50 mL centrifuge tube. Then, 10 mL of acetonitrile (1% acetic acid) was added, and the mixture was vigorously shaken for 1 minute. For liquid-liquid partitioning, a buffered salt mixture comprising 0.5 g anhydrous $MgSO_4$, 0.1 g NaCl, and 0.15 g sodium acetate was added to the initial slurry. The tube was vigorously shaken manually for 1 minute and centrifuged at 2000 rpm for 1 minute. An aliquot of the resulting acetonitrile layer was then subjected to a dispersive solid-phase extraction (d-SPE) clean-up by transferring it to a tube containing 0.05 g primary-secondary amine (PSA), 0.15 g $MgSO_4$, and 0.05 g activated charcoal per mL of extract. This mixture was vortexed for 30 seconds and centrifuged at 3000 rpm for 5 minutes. The final supernatant was filtered through a 0.2 µm PVDF syringe filter prior to analysis. Finally, the solvent was completely evaporated under a nitrogen stream, and the dry residue was dissolved in a known volume of acetone for analysis by GC-MS.

Instrumental analysis

The extraction and clean-up of tomato samples were performed using a modified QuEChERS The analysis of pesticide residues was carried out using gas chromatography coupled with mass spectrometry (GC-MS). The analysis was performed on a Thermo Scientific TRACE

1300 series GC equipped with a TG-5MS capillary column (30 m × 0.25 mm i.d. × 0.25 µm film thickness) with a (5%-phenyl)-methylpolysiloxane stationary phase. The carrier gas was helium (99.999% purity) at a constant flow rate of 1.0 mL/min. The temperature program for the GC oven was as follows: initial temperature 60°C (held for 1 min), increased to 180°C at a rate of 25°C/min, then to 280°C at a rate of 5°C/min (held for 5 min). The injection volume was 1 µL in a split mode with a high split ratio of 50:1 and, with an injector temperature of 250°C. Mass spectrometric detection was performed using a Thermo Scientific ISQ QD single quadrupole mass spectrometer. The transfer line and ion source temperatures were maintained at 280°C and 250°C, respectively. Electron ionization (EI) was conducted at 70 eV. The mass spectrometer was set to scan mode, acquiring data over a mass-to-charge (m/z) range of 50 to 550 atomic mass units (amu). The mass spectra of the eluted compounds were compared with reference spectra in the NIST and Wiley mass spectral libraries (Shellie et al., 2002). The system was tuned and calibrated according to the manufacturer's specifications prior to analysis. Identification was achieved by comparing the retention times and mass spectra of the samples with those of the reference standards using Xcalibur 2.0 software (Thermo Scientific).

RESULTS AND DISCUSSION

Pesticide residue profiling in tomato fruit and regional variation

This study utilized Gas Chromatography-Mass Spectrometry (GC-MS) to determine the pesticide residue profile in tomato fruits from three major agricultural governorates in Egypt: Al-Hadrah (Alexandria), Rosetta (El-Beheira), and Fuwwah (Kafr El Sheikh). The analysis revealed a concerning presence of multiple pesticide residues in all samples, indicating widespread and complex application practices. The GC-MS analysis identified a total of 28 distinct pesticide compounds across the three locations, encompassing various chemical classes including organophosphate, pyrethroid, organochlorine, carbamate, avermectin, triazole, phthalimide, and carboxanilide classes, alongside the synergist piperonyl butoxide (Tables 1-3). While GC-MS area percentages are semi-quantitative and do not equate to concentrations without calibration, they provide relative abundance insights within each chromatogram (Lehotay et al., 2010). Figures 1-3 show the total ion chromatogram (TIC) from GC-MS analysis of the organic compounds identified in a tomato fruit extract from the three agricultural governorates. The three regions shared several high-prevalence organophosphates (malathion, parathion-ethyl, ethion, carbophenothion) and triazole fungicide propiconazole, but differed notably in the prominence of specific actives and the presence of legacy organochlorines (endosulfan) and fungicides (carboxin, captafol, and captan).

Al-Hadrah, Alexandria profile

Based on the data presented in Table 1 and Figure 1, the GC-MS analysis of an extract from tomato fruit samples collected in Al-Hadrah, Alexandria Governorate, revealed a complex profile of pesticide residues. A total of 16 distinct chemical compounds were identified, comprising a mixture of insecticides, acaricides, fungicides, and one synergist. The results indicate a significant pesticide load on the analyzed tomato samples, with the compounds eluting over a wide retention time range from 7.29 to 51.01 minutes. The most prevalent compound detected was chlorpyrifos, an organophosphate insecticide, which constituted the highest relative abundance at 16.53% of the total area. This was followed by diazinon, another organophosphate insecticide, at 7.66%. Other notable constituents included profenofos (6.93%), malathion (6.89%), ethion (6.69%), and cypermethrin (5.79%). The analysis also confirmed the presence of multiple isomers or variants of certain pesticides, specifically malathion, which was detected at two different retention times (10.98 min and 30.94 min) with a combined area percentage of 8.68%. Organophosphate compounds were the dominant chemical class, representing nine of the seventeen identified substances. This class includes diazinon, acephate, malathion, chlorpyrifos, profenofos, parathion-ethyl, ethion, and carbophenothion. Pyrethroid insecticides were also well-represented, with cypermethrin, lambda-cyhalothrin, and deltamethrin identified. Furthermore, the analysis detected the fungicides chlorothalonil and propiconazole, the synergist piperonyl butoxide (often used to enhance the potency of insecticides), and the potent avermectin compound, abamectin. The presence of this diverse array of pesticide residues suggests a history of intensive application of various agrochemicals for pest and disease control in the tomato cultivation practices of this region.

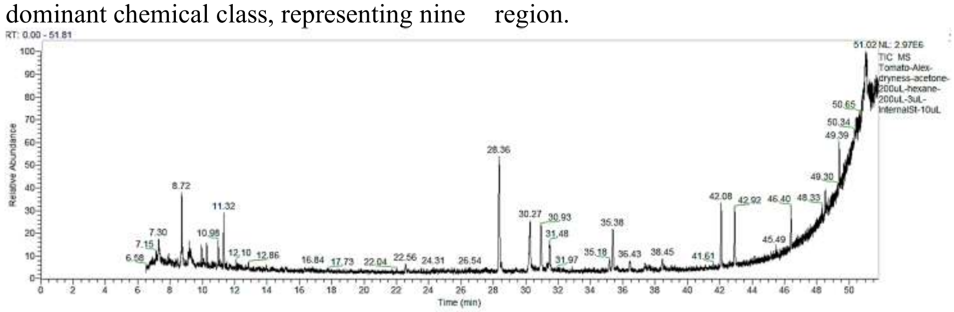

Figure 1. Total ion chromatogram (TIC) from GC-MS analysis of the organic compounds identified in a tomato fruit extract from Al-Hadrah, Alexandria Governorate.

Table 1. GC-MS analysis of the chemical constituents of extract from the tomato fruit samples from Al-Hadrah, Alexandria Governorate

Rt (min)	Area (%)	Compound name	Chemical class	Molecular formula	Molecular weight (g/mol)
7.29	2.70	Chlorothalonil	Fungicide	$C_8Cl_4N_2$	265.91
8.73	7.66	Diazinon	Organophosphate Insecticide	$C_{12}H_{21}N_2O_3PS$	304.35
9.18	1.56	Acephate	Organophosphate Insecticide	$C_4H_{10}NO_3PS$	183.16
10.98	1.79	Malathion (isomer)	Organophosphate Insecticide	$C_{10}H_{19}O_6PS_2$	330.36
11.32	3.19	Abamectin	Avermectin Acaricide/Insecticide	$C_{48}H_{72}O_{14}$ (B1a) / $C_{47}H_{70}O_{14}$ (B1b)	873.09 (B1a avg.)
28.36	16.53	Chlorpyrifos	Organophosphate Insecticide	$C_9H_{11}Cl_3NO_3PS$	350.59
30.26	6.93	Profenofos	Organophosphate Insecticide	$C_{11}H_{15}BrClO_3PS$	373.63

Rt (min)	Area (%)	Compound name	Chemical class	Molecular formula	Molecular weight (g/mol)
30.94	6.89	Malathion	Organophosphate Insecticide	$C_{10}H_{19}O_6PS_2$	330.36
31.49	3.84	Parathion-ethyl	Organophosphate Insecticide	$C_{10}H_{14}NO_5PS$	291.26
35.38	5.79	Cypermethrin	Pyrethroid Insecticide	$C_{22}H_{19}Cl_2NO_3$	416.30
42.08	6.69	Ethion	Organophosphate Acaricide/Insecticide	$C_9H_{22}O_4P_2S_4$	384.48
42.92	5.98	Carbophenothion	Organophosphate Acaricide/Insecticide	$C_{11}H_{16}ClO_2PS_3$	342.86
46.40	3.58	Lambda-cyhalothrin	Pyrethroid Insecticide	$C_{23}H_{19}ClF_3NO_3$	449.85
48.52	2.09	Piperonyl Butoxide	Synergist	$C_{19}H_{30}O_5$	338.44
49.38	3.58	Deltamethrin	Pyrethroid Insecticide	$C_{22}H_{19}Br_2NO_3$	505.20
51.01	4.75	Propiconazole	Triazole Fungicide	$C_{15}H_{17}Cl_2N_3O_2$	342.22

Rosetta, El-Beheira profile

Based on the GC-MS analysis of an extract from tomato fruit samples collected in Rosetta, El-Beheira Governorate, the chemical profile was found to be complex and dominated by a variety of pesticide residues (Table 2 and Figure 2). A total of 19 distinct compounds were identified, with the fungicide carboxin being the most predominant constituent, representing 12.46% of the total detected area. The triazole fungicide propiconazole was also a major component, detected at a significant level of 11.68%. Other notable compounds included malathion (5.31%), ethion (4.76%), carbophenothion (4.20%), and cycloheximide (3.63%), indicating a substantial pesticide load on the analyzed fruit samples. Organophosphates like malathion (5.31%) and ethion (4.76%) were also present but at lower relative abundances compared to Al-Hadrah. The chemical classes of the identified compounds reveal a heavy reliance on synthetic pesticides in the cultivation of these tomatoes. Organophosphate insecticides and acaricides were the most frequently detected class, with six representatives: phoxim, malathion, parathion-ethyl, dimethoate, ethion, and carbophenothion. Fungicides were also highly prevalent and diverse, encompassing phthalimides (captan and captafol), triazoles (propiconazole and triadimefon), a carboxanilide (carboxin), and others like chlorothalonil and cycloheximide. Furthermore, the presence of older, more persistent chemicals was confirmed by the detection of organochlorine insecticides (alpha-endosulfan and endosulfan), along with a pyrethroid insecticide (permethrin) and the common synergist piperonyl butoxide.

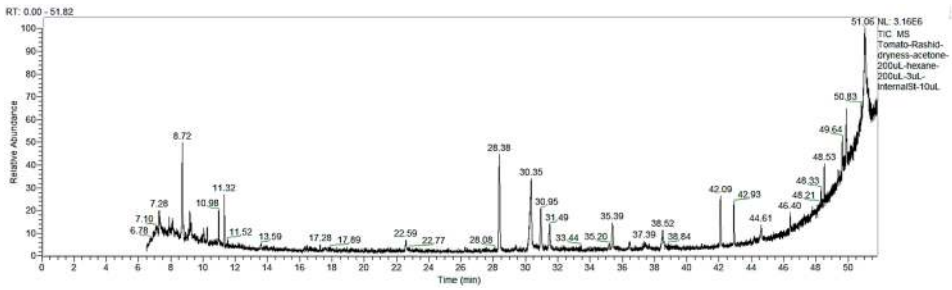

Figure 2. Total ion chromatogram (TIC) from GC-MS analysis of the organic compounds identified in a tomato fruit extract from Rosetta, El-Beheira Governorate.

Table 2. GC-MS analysis of the chemical constituents of extract from the tomato fruit samples from Rosetta, El-Beheira Governorate

Rt (min)	Are a (%)	Compound name	Chemical class	Molecular formula	Molecul ar weight (g/mol)
7.29	2.96	Chlorothalonil	Fungicide	$C_8Cl_4N_2$	265.91
8.11	2.21	Alpha-Endosulfan	Organochlorine Insecticide	$C_9H_6Cl_6O_3S$	406.92
10.27	1.30	Captan	Phthalimide Fungicide	$C_9H_8Cl_3NO_2S$	300.59
11.32	2.77	Abamectin	Avermectin Acaricide/Insecticide	$C_{48}H_{72}O_{14}$	872.09
22.59	1.40	Phoxim	Organophosphate Insecticide	$C_{12}H_{15}N_2O_3PS$	298.30
28.38	12.46	Carboxin	Carboxanilide Fungicide	$C_{12}H_{13}NO_2S$	235.31
30.95	5.31	Malathion	Organophosphate Insecticide	$C_{10}H_{19}O_6PS_2$	330.36
31.49	3.05	Parathion-ethyl	Organophosphate Insecticide	$C_{10}H_{14}NO_5PS$	291.26
35.39	3.63	Cycloheximide	Antibiotic/Fungicide	$C_{15}H_{23}NO_4$	281.35
36.45	1.69	Dimethoate	Organophosphate Insecticide	$C_5H_{12}NO_3PS_2$	229.26
38.52	2.76	Captafol	Phthalimide Fungicide	$C_{10}H_9Cl_4NO_2S$	349.06
42.09	4.76	Ethion	Organophosphate Acaricide/Insecticide	$C_9H_{22}O_4P_2S_4$	384.48
42.93	4.20	Carbophenothion	Organophosphate Acaricide/Insecticide	$C_{11}H_{16}ClO_2PS_3$	342.86
44.61	1.85	Pyrazophos	Organophosphate Fungicide	$C_{14}H_{20}N_3O_5PS$	373.37
46.40	1.45	Triadimefon	Triazole Fungicide	$C_{14}H_{16}ClN_3O_2$	293.75
48.33	1.72	Permethrin	Pyrethroid Insecticide	$C_{21}H_{20}Cl_2O_3$	391.29
48.53	2.62	Piperonyl Butoxide	Synergist	$C_{19}H_{30}O_5$	338.44
50.38	1.30	Endosulfan	Organochlorine Insecticide	$C_9H_6Cl_6O_3S$	406.92
51.05	11.68	Propiconazole	Triazole Fungicide	$C_{15}H_{17}Cl_2N_3O_2$	342.22

Fuwwah, Kafr El Sheikh profile

The GC-MS analysis of the sample from Fuwwah, Kafr El Sheikh governorate, revealed a concerning profile, as the tomato fruit extract was composed entirely of pesticide residues along with the antibiotic cycloheximide, indicating a significant and extensive history of agrochemical application (Table 3 and Figure 3). The major chemical classes identified were dominated by organophosphates, with eight different compounds detected that constituted the majority of the total residue by relative abundance. Other classes included two carbamates (carbaryl and carbofuran), two pyrethroids (lambda-cyhalothrin and deltamethrin), as well as one organochlorine (endosulfan), one avermectin (abamectin), and the aforementioned antibiotic. The most prevalent individual compounds were all organophosphates, namely Ethion (19.02%), carbophenothion (18.42%), malathion (11.60%), and parathion-ethyl (9.18%), which together account for over half (58.22%) of the total detected constituents. Alarmingly, the analysis detected several high-hazard pesticides, including parathion-ethyl, carbofuran, and endosulfan, which are known for their high toxicity and are restricted or banned in many countries due to environmental persistence and serious health risks. This geographical location also contained carbamate insecticides (carbaryl and carbofuran), which were not detected in the other two locations.

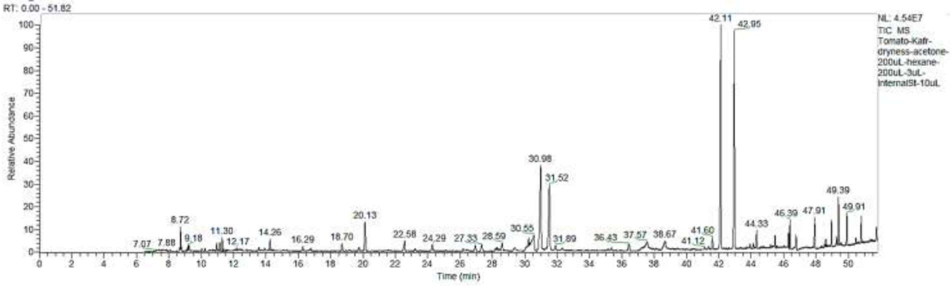

Figure 3. Total ion chromatogram (TIC) from GC-MS analysis of the organic compounds identified in a tomato fruit extract from Fuwwah, Kafr El Sheikh Governorate.

Table 3. GC-MS analysis of the chemical constituents of extract from the tomato fruit samples from Al- Fuwwah, Kafr El Sheikh Governorate

Rt (min)	Area (%)	Compound name	Chemical class	Molecular formula	Molecular weight (g/mol)
8.72	1.73	Diazinon	Organophosphate Insecticide	$C_{12}H_{21}N_2O_3PS$	304.35
9.25	0.49	Carbaryl	Carbamate Insecticide	$C_{12}H_{11}NO_2$	201.22
11.15	0.55	Azinphos-methyl	Organophosphate Insecticide	$C_{10}H_{12}N_3O_3PS_2$	317.32
11.30	0.72	Abamectin	Avermectin Acaricide/Insecticide	$C_{48}H_{72}O_{14}$	872.09
20.13	3.32	Cycloheximide	Antibiotic/Fungicide	$C_{15}H_{23}NO_4$	281.35
24.28	0.78	Carbofuran	Carbamate Insecticide	$C_{12}H_{15}NO_3$	221.25
30.98	11.60	Malathion	Organophosphate Insecticide	$C_{10}H_{19}O_6PS_2$	330.36

Rt (min)	Area (%)	Compound name	Chemical class	Molecular formula	Molecular weight (g/mol)
31.52	9.18	Parathion-ethyl	Organophosphate Insecticide	$C_{10}H_{14}NO_5PS$	291.26
36.43	1.00	Dimethoate	Organophosphate Insecticide	$C_5H_{12}NO_3PS_2$	229.26
42.11	19.02	Ethion	Organophosphate Acaricide/Insecticide	$C_9H_{22}O_4P_2S_4$	384.48
42.95	18.42	Carbophenothion	Organophosphate Acaricide/Insecticide	$C_{11}H_{16}ClO_2PS_3$	342.86
44.33	1.44	Pyrazophos	Organophosphate Fungicide	$C_{14}H_{20}N_3O_5PS$	373.37
46.39	1.87	Lambda-cyhalothrin	Pyrethroid Insecticide	$C_{23}H_{19}ClF_3NO_3$	449.85
49.26	0.65	Endosulfan	Organochlorine Insecticide	$C_9H_6Cl_6O_3S$	406.92
49.39	2.79	Deltamethrin	Pyrethroid Insecticide	$C_{22}H_{19}Br_2NO_3$	505.21

Cross-regional analysis and chemical class prevalence

A critical observation across all samples was the detection of multiple compounds from the same class, indicating the application of pesticide cocktails. A unifying feature across all three regions was the ubiquitous presence and high relative abundance of organophosphate pesticides (OPs). Compounds such as chlorpyrifos, diazinon, malathion, parathion-ethyl, and ethion were detected in all or most of the samples. OPs are broad-spectrum insecticides that act by inhibiting acetylcholinesterase, a crucial enzyme for nerve function in both insects and humans, leading to acute neurotoxicity (Eaton et al., 2008). The prevalence of OPs reflects their cost-effectiveness and widespread availability in developing countries, but it also raises significant public health concerns due to their high acute toxicity and potential for chronic neurological effects, especially in agricultural workers (Perry et al., 2020).

Pyrethroid insecticides were detected in Al-Hadrah and Fuwwah, contributing to the chemical load. While generally considered less acutely toxic to mammals than OPs, some pyrethroids are suspected endocrine disruptors and are highly toxic to aquatic organisms and beneficial insects like bees (Brander et al., 2016; Liu et al., 2022). The co-occurrence of OPs and pyrethroids can also lead to complex toxicological interactions.

The detection of organochlorines (endosulfan) in Rosetta and Fuwwah is a critical finding. Their extreme persistence in the environment means they can continue to contaminate crops long after their use has ceased, representing a long-term source of exposure (Kumar and Mukherji, 2018). Similarly, the detection of carbamate insecticides (carbaryl, carbofuran) in Fuwwah adds to the toxicological burden, as carbamates also inhibit acetylcholinesterase, though with a shorter duration of action than organophosphates.

Implications for food safety and regulatory compliance

The detection of multiple pesticide residues, including several with strict regulatory limits, raises significant food safety concerns. Compounds such as chlorpyrifos, diazinon, and malathion were found in all regions, and their residues are subject to Maximum Residue Limits (MRLs) established by the Codex Alimentarius Commission and importing regions like the European Union (EU). The use of chlorpyrifos, in particular, has been severely restricted or banned in the EU and other countries due to concerns about its potential neurodevelopmental toxicity (EFSA et al., 2019). The detection of parathion-ethyl, a highly toxic organophosphate that is banned in many countries, is especially alarming.

The high frequency and abundance of OPs across all three locations is the most alarming finding. OPs, such as chlorpyrifos, diazinon, and malathion, function by inhibiting the enzyme acetylcholinesterase, leading to the accumulation of acetylcholine and resulting in neurotoxicity (Aroniadou-Anderjaska et al., 2023). Chronic exposure to low levels of OPs has been associated with neurological developmental deficits in children, endocrine disruption, and an increased risk of certain cancers (Muñoz-Quezada et al., 2013). The detection of Parathion-ethyl in all three governorates is particularly concerning. This compound is classified as highly hazardous by the WHO and is banned or severely restricted in many countries due to its high acute toxicity to humans (WHO, 2018). Similarly, the presence of carbamates (carbofuran, carbaryl) in Fuwwah adds to the neurotoxic risk, as they share a similar mechanism of action with OPs.

The identification of endosulfan (and its isomer alpha-endosulfan) in the Rosetta and Fuwwah samples represents a major regulatory and environmental concern. Endosulfan is a persistent organic pollutant (POP) listed for elimination under the Stockholm Convention due to its toxicity, persistence in the environment, and ability to bioaccumulate in the food chain (Weber et al., 2010). Its detection indicates the possible use of obsolete stockpiles or a clear violation of international and national bans, posing long-term ecological and health risks.

The high relative abundance of fungicides, particularly in Rosetta (propiconazole, Carboxin), points to significant challenges with fungal diseases. The coexistence of fungicides from different chemical groups (e.g., triazoles, carboxanilides, phthalimides like captan and captafol) could be a strategy to manage fungicide resistance. However, the application of such a complex mixture, especially with compounds like propiconazole which has specific restrictions due to its environmental persistence, indicates a heavy reliance on chemical control, which is unsustainable in the long term (Brent and Hollomon, 1995).

The use of pyrethroid insecticides (e.g., cypermethrin, deltamethrin, lambda-cyhalothrin) is evident, particularly in Al-Hadrah and Fuwwah. Pyrethroids are generally less acutely toxic to mammals than OPs. However, their co-detection with the synergist piperonyl butoxide (PBO) is a significant practice. PBO inhibits cytochrome P450 enzymes, which are responsible for metabolizing and detoxifying pyrethroids in both pests and non-target organisms, thereby increasing the insecticides' potency (Basak et al., 2021). This practice raises questions about the potential for increased residual toxicity and the impact on non-target organisms, including humans.

While the present study provides a comprehensive qualitative and semi-quantitative (area %) profile, a full risk assessment requires the quantification of residues in units of mg/kg to enable direct comparison with established MRLs (Pihlström et al., 2021). The co-occurrence of multiple residues, a phenomenon known as the "pesticide cocktail," also necessitates the consideration of potential cumulative and synergistic effects, which are not typically addressed in single-chemical risk assessments (Badder, 2023). The high prevalence of residues in a staple food like tomatoes, which are consumed fresh and in large quantities, underscores the potential for significant dietary exposure among the Egyptian population.

CONCLUSION

This study reveals a critical public health and regulatory issue, demonstrating that tomatoes from three major Egyptian regions are pervasively contaminated with complex mixtures of pesticide residues. The residue analysis was performed by GC-MD and the most alarming findings are the ubiquitous presence of neurotoxic organophosphate insecticides, including the banned parathion-ethyl, and the detection of the banned persistent organic pollutant endosulfan, indicating a severe breach of international standards. While regional variations exist, such as a dominance of insecticides in Al-Hadrah, fungicides in Rosetta, and acaricides in Fuwwah, all areas exhibit a hazardous reliance on "pesticide cocktails." This practice, combined with the use of synergists, raises serious concerns about unknown cumulative toxicological effects. Urgent actions are required, including stringent regulatory enforcement to remove banned substances, a fundamental shift towards Integrated Pest Management (IPM) protocol. Promoting IPM can reduce reliance on hazardous chemicals, mitigate risks to human health and the environment, and ensure the safety and competitiveness of Egypt's agricultural exports in the global market. Ultimately, addressing this pervasive contamination demands a concerted effort to transition towards safer, sustainable agricultural practices that protect both consumer health and environmental integrity.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Availability of data and materials

The data that support the findings of this study are available from the corresponding author, Mohamed E. I. Badawy upon reasonable request.

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دراسة مقارنة لتحليل بقايا المبيدات المتعددة في ثمار الطماطم من مناطق زراعية مختلفة في مصر

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تقدم هذه الدراسة تحليلاً شاملاً لبقايا المبيدات في ثمار الطماطم من ثلاث محافظات زراعية رئيسية في مصر: الحضرة (الإسكندرية)، ورشيد (البحيرة)، وفوة (كفر الشيخ) .باستخدام تقنية كروماتوغرافي الغاز-مطياف الكتلة (GC-MS). كشف التحليل عن انتشار مثير للقلق لتلوث المبيدات في جميع المناطق. تم تحديد مركبات مبيدات مختلفة، تشمل الفوسفور العضوية، والبيرثرويدات، والكلور العضوي، والكربامات، والترايازولات، وفئات كيميائية أخرى .تشير النتائج إلى تباين إقليمي كبير في خصائص المبيدات .كانت عينات الحضرة مشبعة بالفوسفور العضوية مثل الكلوربيريفوس (بنسبة 16.53% كمساحة بيك)، بينما أظهرت عينات رشيد تركيزات عالية من مبيدات الفطريات، يتصدرها الكاربوكسين (12.46%)، بينما أظهرت عينات فوّه مستوىً مثيرًا للقلق، يتكون بالكامل من بقايا مبيدات الآفات، تهيمن عليه بشكل كبير الفوسفور العضوية مثل الإيثيون (19.02%) . ومن النتائج الإقليمية الحاسمة الانتشار الواسع والوفرة النسبية العالية لمبيدات الحشرات العضوية الفوسفاتية، مما أثار مخاوف صحية عامة كبيرة نظرًا لسميتها العصبية الحادة .كما كشفت الدراسة عن العديد من مبيدات الآفات المحظورة أو شديدة الخطورة، بما في ذلك الباراثيون-إيثيل (في جميع المناطق) والملوث العضوي الثابت إندوسلفان (في رشيد وفوّه)، مما يشير إلى احتمال عدم الامتثال للوائح التنظيمية واستخدام مخزونات قديمة .ويؤكد الكشف الروتيني عن "مزيجات" معقدة من المبيدات، إلى جانب استخدام مواد تآزرية مثل بيبيرونيل بوتوكسيد، على احتمالية حدوث آثار سمية تراكمية وتآزرية .تُسلّط هذه النتائج الضوء على ممارسات استخدام الكيماويات الزراعية واسعة النطاق والمكثفة، مما يُشكّل مخاطر جسيمة على سلامة الغذاء وتهديدات صحية محتملة للمستهلكين .وتُبرز الدراسة الحاجة المُلحّة إلى تعزيز إنفاذ اللوائح، والرقابة، وتعزيز استراتيجيات الإدارة المتكاملة المستدامة للآفات في زراعة الطماطم في مصر.