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Multi-residue screening of pesticides from different geographical regions in Egypt: A case study of guava fruit

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ABSTRACT

This study investigated the profile and regional variation of pesticide residues and contaminants in guava fruits cultivated in three major Egyptian governorates: Al-Hadrah (Alexandria), Rosetta (El-Beheira), and Fuwwah (Kafr El Sheikh). Using Gas Chromatography-Mass Spectrometry (GC-MS) analysis, a total of 24 distinct chemical compounds were identified, revealing significant contamination and diverse agricultural practices across the regions. The sample from Al-Hadrah exhibited the most complex profile with 18 compounds, followed by Rosetta (13) and Fuwwah (11). Synthetic pyrethroids, particularly lambda-cyhalothrin (the most abundant compound in two regions, up to 41.87%) and deltamethrin, were overwhelmingly dominant. The analysis also detected concerning levels of organophosphates (e.g., diazinon, dimethoate, and malathion) and carbamates (e.g., carbofuran), whose co-occurrence raises the risk of additive toxic effects. Furthermore, fungicides (chlorothalonil, and captan) and the plant growth regulator maleic hydrazide were consistently detected. A critical finding was the identification of the plasticizer dibutyl phthalate at high concentrations (up to 18.97%), indicating potential post-harvest or environmental contamination. The results highlight serious implications for food safety and regulatory compliance. The high residue levels, the presence of highly toxic compounds like carbofuran, and the complex mixture of pesticides with similar modes of action suggest a likely exceedance of Maximum Residue Limits (MRLs) and pose potential health risks from both acute and chronic exposure. The study concludes that intensive pesticide use in Egyptian guavas creates a hazardous residue cocktail, demanding stricter regulation, farmer education on safer practices, and expanded food safety monitoring.

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

INTRODUCTION

Guava (*Psidium guajava* L.), a fruit widely cultivated in tropical and subtropical regions, is valued for its distinctive flavor and significant nutritional content, including high levels of vitamins A and C, dietary fiber, and antioxidants (Angulo-López et al., 2021; Hussain et al., 2021). In Egypt, guava has become a crop of significant economic importance, with expanding cultivation areas in regions such as the Nile Delta, Upper Egypt, and newly reclaimed lands, catering to both local consumption and

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export markets. The increasing demand for high-quality, blemish-free fruit has led to an intensive application of pesticides to control a wide range of insect pests and fungal diseases that can affect yield and visual quality (Ibrahim et al., 2022).

The use of pesticides, while beneficial for securing harvests, raises considerable public health and environmental concerns. Pesticide residues can persist on or in agricultural commodities and may pose acute or chronic risks to consumers, including potential carcinogenic, neurotoxic, and endocrine-disrupting effects (Ali et al., 2020; Hamilton et al., 2004). To mitigate these risks, many countries and international bodies, such as the European Union and the Codex Alimentarius, have established Maximum Residue Limits (MRLs) for pesticides in food commodities. Compliance with these MRLs is not only a public health imperative but also a critical requirement for international trade, where non-compliance can result in the rejection of shipments and significant economic losses for exporting nations (Fantke et al., 2012).

In Egypt, the pattern of pesticide use can vary substantially across different geographical regions due to factors such as local pest pressures, climatic conditions, farmer knowledge, and the availability of specific agrochemicals. These regional disparities can lead to distinct pesticide residue profiles in the final produce (Alla et al., 2013; Dogheim et al., 2002; Malhat et al., 2022). While several studies have monitored pesticide residues in various fruits and vegetables in Egypt, there is a paucity of comprehensive data focusing specifically on guava and how residue levels may differ across the country's major growing areas. A multi-residue screening approach is essential for this purpose, as it allows for the simultaneous detection and quantification of dozens to hundreds of pesticide compounds in a single analytical run (Anagnostopoulos and Miliadis 2013).

Therefore, this study aims to conduct a comprehensive multi-residue screening of pesticides in guava fruits collected from three major agricultural governorates in the Nile Delta region of Egypt: Al-Hadrah (Alexandria Governorate), Rosetta (El-Beheira Governorate), and Fuwwah (Kafr El Sheikh Governorate). The specific objectives are to: (1) identify the most common pesticide residues present in Egyptian guava from these key production areas, and (2) compare the residue profiles across these different growing regions to identify geographical trends. The findings from this case study will provide valuable data for Egyptian regulatory authorities, farmers, and exporters to promote safer pesticide practices and ensure the production of guava that meets both domestic and international food safety standards.

MATERIALS AND METHODS

Chemicals and reagents

Pesticide analytical standards (≥98% purity) for 35 compounds, including organophosphates, carbamates, pyrethroids, and neonicotinoids, were obtained from Dr. Ehrenstorfer GmbH (Augsburg, Germany). HPLC-grade solvents (acetone, acetonitrile, hexane, methanol, and water) were purchased from Merck (Darmstadt, Germany). Sample preparation utilized primary secondary amine (PSA, 40 μm; Supelco, USA), polyvinylidene fluoride (PVDF) syringe filters (0.2 μm; Whatman, USA), and the following reagents from El-Nasr

Pharmaceutical Chemicals Co. (Egypt): anhydrous magnesium sulfate, sodium chloride, sodium acetate, and activated charcoal. Individual pesticide stock solutions (1000 µg/mL) were prepared in acetonitrile and stored at -20°C, with working standard mixtures prepared fresh by dilution on the day of use.

Sample collection

Guava fruit (*Psidium guajava* L.) samples were collected from three major agricultural governorates in the Nile Delta region of Egypt: Al-Hadrah (Alexandria Governorate), Rosetta (El-Beheira Governorate), and Fuwwah (Kafr El Sheikh Governorate). These locations were selected to represent key guava production areas with potentially varying agricultural practices and pest management strategies. A total of 15 guava samples (5 from each region, 1 kg per each sample) were randomly collected during the peak harvesting season (September-November 2022) from local farms from each governorate. Sampling was designed to be representative of the fruit available to consumers. Samples were selected to represent common commercial varieties and were immediately transported to the laboratory in sterile polyethylene bags under cold chain conditions (4°C).

Sample preparation

Upon arrival at the laboratory, the entire contents of each composite sample (including peel and pulp) were homogenized using a high-speed commercial stainless-steel blender. This process ensured a homogeneous and representative matrix for analysis. A portion of this homogenate was immediately used for extraction, and the remainder was stored at -20°C in pre-cleaned glass jars to await analysis and for any necessary future verification. This freezing step effectively halts enzymatic and microbial activity that could alter the pesticide residue profile.

Sample extraction and clean-up

The extraction and clean-up of pesticides from homogenized guava pulp were performed using a modified QuEChERS method (Anastassiades et al., 2007; Payá et al., 2007). Briefly, a 2 g sample homogenate was weighed into a 50 mL centrifuge tube and extracted with 10 mL of acidified acetonitrile (1% acetic acid) by vigorous shaking. A buffered salt mixture (0.5 g $MgSO_4$, 0.1 g NaCl, 0.15 g sodium acetate) was added to induce liquid-liquid partitioning. The tube was shaken, centrifuged, and an aliquot of the acetonitrile layer was subjected to a dispersive solid-phase extraction (d-SPE) clean-up using a mixture of primary-secondary amine (PSA), $MgSO_4$, and activated charcoal. After vortexing and centrifugation, the supernatant was filtered through a 0.2 µm PVDF syringe filter. The extract was then concentrated under a gentle nitrogen stream, and the residue was reconstituted in a known volume of acetone for subsequent GC-MS analysis.

GC-MS analysis

Pesticide residue analysis was conducted using GC-MS on a Thermo Scientific TRACE 1300 series system coupled to an ISQ QD single quadrupole mass spectrometer. Separation was achieved on a TG-5MS capillary column (30 m × 0.25 mm i.d. × 0.25 µm film thickness) with helium as the carrier gas with average velocity 39 cm/s at a constant flow of 1.0 mL/min. The oven temperature program was initialized at 50°C (held for 1 min), ramped to 150°C at 25°C/min, then to 280°C at 5°C/min (held for 5 min). A 1 µL sample was injected in a splitless mode with an injector temperature of 230°C. The mass spectrometer operated in electron ionization (EI) mode at 70 eV. The ion source and transfer line temperatures were set to 250°C and 200°C, respectively. Data were acquired in scan mode over a mass range of 50-600 (m/z). Compounds were identified by comparing their mass spectra and Linear Retention Indices (LRI), calibrated using a C_8-C_{24} n-alkane series via the Van den Dool and Kratz method (Van Den Dool and Kratz 1963), against authentic reference standards using Xcalibur 2.0 software. The system was tuned and calibrated according to manufacturer specifications prior to analysis.

RESULTS AND DISCUSSION

Pesticide detection frequency and occurrence in guava fruit

GC-MS analysis was employed to identify and quantify the chemical constituents, primarily pesticide residues and contaminants, in guava fruit samples collected from three different geographical locations in Egypt: Al-Hadrah (Alexandria Governorate), Rosetta (El-Beheira Governorate), and Fuwwah (Kafr El Sheikh Governorate). The results, presented in Tables 1, 2, and 3, reveal a complex profile of synthetic chemicals, indicating significant and varied pesticide application practices across the regions. The total ion chromatograms (TIC) from GC-MS analysis of tomato fruit extracts from three governorates are presented in Figures 1-3.

Al-Hadrah, Alexandria pesticide residue profile

The chemical composition of the organic extract from guava samples collected in Al-Hadrah, Alexandria Governorate, was characterized using GC-MS. The analysis revealed a complex mixture of pesticide residues and other organic compounds, as detailed in Table 1 and visualized in the total ion chromatogram (TIC) presented in Figure 1. The GC-MS analysis identified 18 distinct compounds, predominantly consisting of synthetic pesticides from various chemical classes. The most abundant constituent was the pyrethroid insecticide lambda-cyhalothrin, which constituted 41.87% of the TIC area. This was followed by another pyrethroid, deltamethrin (10.98%), and the fungicide captan (6.35%). Maleic hydrazide, a plant growth regulator, was also detected at a significant level of 5.56%. The remaining compounds were present at lower relative abundances, each contributing less than 4% to the total TIC area, with Pendimethalin and azinphos-methyl being the least abundant at 0.35% and 0.42%, respectively. The chromatographic profile in Figure 1 shows a dense cluster of peaks eluting between approximately 17 and 22 minutes, which corresponds to the majority of the high-intensity pesticides identified, including lambda-cyhalothrin, deltamethrin, and fenvalerate. The analysis spanned a wide retention time range from 6.68 to 47.35 minutes, with corresponding Linear Retention Indices (LRI) ranging from 980 to 5047, confirming the presence of compounds with a broad spectrum of volatilities and polarities.

Rosetta, El-Beheira pesticide residue profile

GC-MS analysis was employed to identify and quantify the pesticide residues present in the guava fruit sample collected from Rosetta, El-Beheira Governorate. The results of this analysis are summarized in Table 2, which details the retention time (Rt), relative abundance, compound name, molecular formula, and molecular weight for each identified constituent. The corresponding TIC is presented in Figure 2. The analysis revealed a complex profile of multiple pesticide residues. A total of thirteen distinct chemical compounds were identified. The most abundant compound detected was lambda-cyhalothrin, a synthetic pyrethroid insecticide, which constituted 29.55% of the total ion chromatogram area. Malathion, an organophosphate insecticide, was the second most prevalent compound at 12.08%. Other notable constituents included deltamethrin (8.81%), captan (5.40%), diazinon (3.67%), and maleic hydrazide (3.25%). The remaining compounds, namely metolcarb, chlorothalonil, cypermethrin, acetamiprid, dimethoate, pendimethalin, and dibutyl phthalate, were each present at relative abundances below 3%. The chromatographic separation, as visualized in Figure 2, shows a series of peaks eluting between approximately 6.65 and 39.50 minutes, corresponding to the retention times listed in Table 2. The prominent peak observed at a retention time of 17.40 minutes aligns with the high relative abundance of lambda-cyhalothrin, confirming it as the major residue in the extract. The diversity of compounds identified, belonging to different chemical classes such as pyrethroids, organophosphates, and carbamates, indicates a multi-pesticide residue profile in the analyzed guava sample.

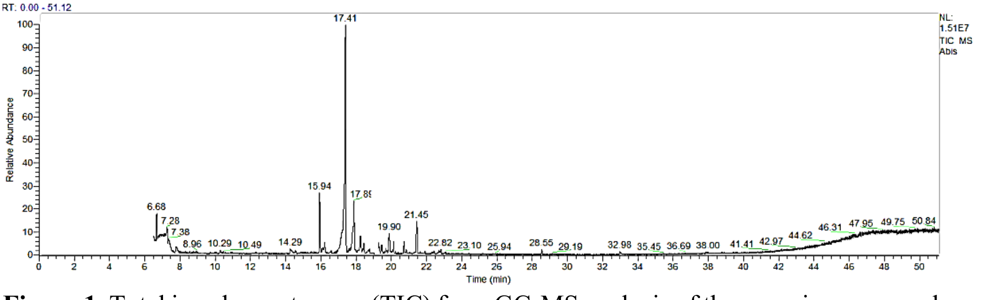

Figure 1. Total ion chromatogram (TIC) from GC-MS analysis of the organic compounds identified in a guava fruit extract from Al-Hadrah, Alexandria Governorate.

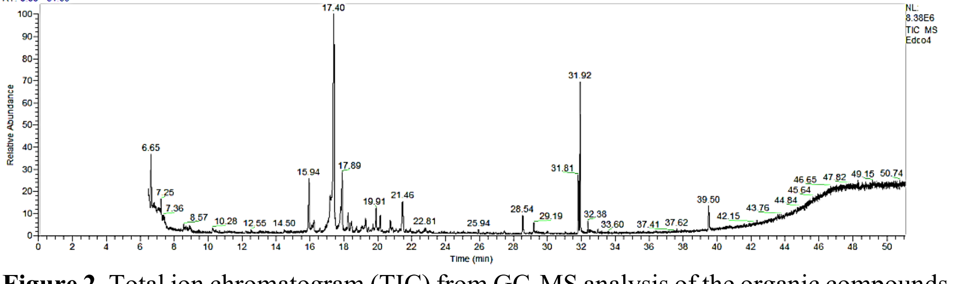

Figure 2. Total ion chromatogram (TIC) from GC-MS analysis of the organic compounds identified in a guava fruit extract from Rosetta, El-Beheira Governorate.

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

Rt (min)	Area[a] (%)	Compound name	Molecular formula	Molecular weight (g/mol)	LRI[b]
6.68	5.56	Maleic hydrazide	$C_4H_4N_2O_2$	112	980
7.19	3.11	Chlorothalonil	$C_8Cl_4N_2$	266	1031
7.37	2.07	Captafol	$C_{10}H_9Cl_4FNO_2S$	347	1049
14.56	0.53	Dimethoate	$C_5H_{12}NO_3PS_2$	229	1768
15.94	6.35	Captan	$C_9H_8Cl_3NO_2S$	299	1906
16.23	2.36	Cypermethrin	$C_{22}H_{19}Cl_2NO_3$	416	1935
17.41	41.87	Lambda-cyhalothrin	$C_{23}H_{19}ClF_3NO_3$	449	2053
17.89	10.98	Deltamethrin	$C_{22}H_{19}Br_2NO_3$	505	2101
18.26	2.20	Bufencarb	$C_{13}H_{19}NO_2$	221	2138
18.45	1.13	Promecarb	$C_{12}H_{17}NO_2$	207	2157
19.08	0.82	Acetamiprid	$C_{10}H_{11}ClN_4$	222	2220
19.71	0.62	Triazophos	$C_{12}H_{16}N_3O_3PS$	313	2283
19.90	2.52	Fenvalerate	$C_{25}H_{22}ClNO_3$	419	2302
20.14	1.47	Amitraz	$C_{19}H_{23}N_3$	293	2326
20.73	1.18	Allethrin	$C_{19}H_{26}O_3$	302	2385
21.45	3.99	Diazinon	$C_{12}H_{21}N_2O_3PS$	304	2457
28.55	0.35	Pendimethalin	$C_{13}H_{19}N_3O_4$	281	3167
47.35	0.42	Azinphos-methyl	$C_{10}H_{12}N_3O_3PS_2$	317	5047

[a] Values are expressed as relative peak-area percentages (%) of the total ion chromatogram (TIC). [b] Linear retention index based on Van den Dool & Kratz method, calculated on a 5% diphenyl:95% dimethyl polysiloxane column (30 m × 0.25 mm i.d., 0.25 µm film thickness) programmed from 50°C to 280°C (10 min) at 5.0°C/min.

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

Rt (min)	Area (%)	Compound name	Molecular formula	Molecular weight (g/mol)	LRI[b]
6.65	3.25	Maleic hydrazide	$C_4H_4N_2O_2$	112	977
7.12	2.00	Metolcarb	$C_9H_{11}NO_2$	165	1024
7.24	2.41	Chlorothalonil	$C_8Cl_4N_2$	266	1036
15.94	5.40	Captan	$C_9H_8Cl_3NO_2S$	299	1906
16.23	1.22	Cypermethrin	$C_{22}H_{19}Cl_2NO_3$	416	1935
17.40	29.55	Lambda-cyhalothrin	$C_{23}H_{19}ClF_3NO_3$	449	2052
17.89	8.81	Deltamethrin	$C_{22}H_{19}Br_2NO_3$	505	2101
19.08	0.78	Acetamiprid	$C_{10}H_{11}ClN_4$	222	2220
19.29	1.97	Dimethoate	$C_5H_{12}NO_3PS_2$	229	2241
21.46	3.67	Diazinon	$C_{12}H_{21}N_2O_3PS$	304	2458
28.54	1.23	Pendimethalin	$C_{13}H_{19}N_3O_4$	281	3166
31.92	12.08	Malathion	$C_{10}H_{19}O_6PS_2$	330	3504
39.50	1.94	Dibutyl phthalate	$C_{16}H_{22}O_4$	278	4262

[a] Values are expressed as relative peak-area percentages (%) of the total ion chromatogram (TIC). [b] Linear retention index based on Van den Dool & Kratz method, calculated on a 5% diphenyl:95% dimethyl polysiloxane column (30 m × 0.25 mm i.d., 0.25 µm film thickness) programmed from 50°C to 280°C (10 min) at 5.0°C/min.

Fuwwah, Kafr El Sheikh pesticide residue profile

The chemical composition of the organic extract from guava samples collected from Fuwwah, Kafr El Sheikh, was characterized using GC-MS. The resulting TIC is presented in Figure 3, and the identified compounds, along with their Rt, relative abundances, and chemical information, are detailed in Table 3. The analysis revealed a complex mixture of eleven distinct organic compounds. The most abundant constituent was the synthetic pyrethroid insecticide lambda-cyhalothrin, which constituted 29.93% of the total ion count, eluting at a retention time of 17.40 minutes. The second most prevalent compound was the plasticizer dibutyl phthalate (18.97%, Rt 39.50 min), followed by another pyrethroid insecticide, deltamethrin (9.63%, Rt 17.89 min). The fungicide captan was also detected at a notable concentration of 4.75% (Rt 15.94 min). Other compounds identified at lower relative abundances included pesticides such as maleic hydrazide (2.83%), chlorothalonil (2.02%), pendimethalin (2.35%), carbofuran (1.88%), propargite (1.56%), chlorpyrifos (0.57%), and the carbamate insecticide promecarb (0.93%). The identification of these compounds was further supported by the calculation of their LRI, which provide an additional confirmation parameter alongside the mass spectral data.

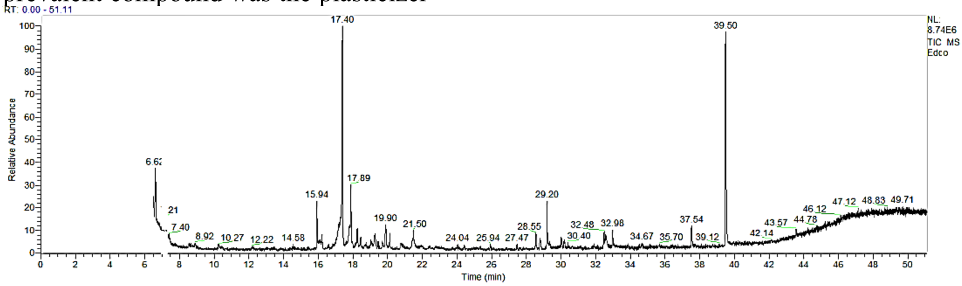

Figure 3. Total ion chromatogram (TIC) from GC-MS analysis of the organic compounds identified in a guava fruit extract from Fuwwah, Kafr El Sheikh Governorate.

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

Rt (min)	Area (%)	Compound name	Molecular formula	Molecular weight (g/mol)	LRI[b]
6.62	2.83	Maleic hydrazide	$C_4H_4N_2O_2$	112	974
7.21	2.02	Chlorothalonil	$C_8Cl_4N_2$	266	1033
15.94	4.75	Captan	$C_9H_8Cl_3NO_2S$	299	1906
17.40	29.93	Lambda-cyhalothrin	$C_{23}H_{19}ClF_3NO_3$	449	2052
17.89	9.63	Deltamethrin	$C_{22}H_{19}Br_2NO_3$	505	2101
18.45	0.93	Promecarb	$C_{12}H_{17}NO_2$	207	2157
19.90	2.35	Pendimethalin	$C_{13}H_{19}N_3O_4$	281	2302
30.03	0.57	Chlorpyrifos	$C_9H_{11}Cl_3NO_3PS$	349	3315
32.98	1.56	Propargite	$C_{19}H_{26}O_4S$	350	3610
37.54	1.88	Carbofuran	$C_{12}H_{15}NO_3$	221	4066
39.50	18.97	Dibutyl phthalate	$C_{16}H_{22}O_4$	278	4262

[a] Values are expressed as relative peak-area percentages (%) of the total ion chromatogram (TIC). [b] Linear retention index based on Van den Dool & Kratz method, calculated on a 5% diphenyl:95% dimethyl polysiloxane column (30 m × 0.25 mm i.d., 0.25 µm film thickness) programmed from 50°C to 280°C (10 min) at 5.0°C/min.

Overall pesticide residue profile and regional variation

The GC-MS analysis revealed a total of 24 distinct chemical compounds across the three guava samples, indicating a concerning level of contamination. A clear regional variation was observed in the complexity of the pesticide profiles. The sample from Al-Hadrah (Table 1) exhibited the most complex contamination, with 18 different compounds detected, followed by Al-Rosetta (Table 2) with 13, and Al-Fuwwah (Table 3) with 11. This gradient suggests significant differences in local agricultural practices, specific pest pressures, and the pesticide regimens employed by farmers in each governorate. The most striking finding across all locations was the overwhelming dominance of synthetic pyrethroid insecticides. Lambda-cyhalothrin was the most abundant compound in Al-Hadrah (41.87%) and Fuwwah (29.93%), and the second most abundant in Rosetta (29.55%), while deltamethrin was also a major constituent in all three samples. This widespread and heavy reliance on pyrethroids is consistent with their broad-spectrum efficacy and their popularity as a replacement for more persistent organochlorine pesticides. However, the notably high concentrations detected raise significant concerns regarding compliance with MRLs and the potential for associated health risks.

Detailed analysis of key chemical classes

The chemical constituents identified in the guava extracts can be grouped into major classes based on their function and toxicological profile, revealing distinct patterns of agricultural use and potential risk.

Synthetic pyrethroids

The most prominent class of compounds in terms of concentration and frequency were the synthetic pyrethroids. Lambda-cyhalothrin was the single most abundant compound found in the Al-Hadrah sample (41.87%) and a major component in the others, while deltamethrin was also consistently present at high levels. These Type II pyrethroids are favored in agriculture for their high insecticidal potency and relatively low acute mammalian toxicity. However, their high relative percentages in the fruit extracts indicate recent and likely intensive application, as they are not highly persistent compounds (Hodoșan et al., 2023; Ravula and Yenugu 2021). Despite their favorable safety profile compared to older pesticides, chronic exposure to pyrethroids has been linked to neurotoxic effects in humans, raising concerns about the long-term implications of such high residue levels (Saillenfait et al., 2015; Vijverberg and vanden Bercken 1990). Furthermore, the Al-Hadrah sample contained additional pyrethroids, namely cypermethrin and fenvalerate. The presence of this multi-pyrethroid cocktail suggests a strategy to combat insect resistance or target a broader spectrum of pests, a practice whose complex toxicological implications are not yet fully understood (Antwi and Reddy 2015).

Organophosphates and carbamates

Another significant group of insecticides identified were acetylcholinesterase inhibitors, comprising organophosphates and carbamates. Among the organophosphates, diazinon was detected in all three locations, while dimethoate was present in Al-Hadrah and Rosetta. Notably, malathion was a major component (12.08%) in the Rosetta sample. Organophosphates are generally more acutely toxic to humans than pyrethroids, and their presence, even at lower relative percentages, is a significant concern due to the potential for cumulative effects from exposure to multiple compounds within this class (Barr and Angerer 2006). Carbamate insecticides were also identified, including bufencarb and promecarb in Al-Hadrah and metolcarb in Rosetta. Of particular concern is the detection of carbofuran in the Fuwwah sample, a carbamate known for its high toxicity. The co-occurrence of organophosphates and carbamates is particularly concerning due to their shared mechanism of action: acetylcholinesterase inhibition (Aroniadou-Anderjaska et al., 2023; Fukuto 1990). This can lead to additive toxic effects, potentially causing acute cholinergic syndrome even when each compound is present below its individual safety threshold.

Fungicides and other pesticides

The analysis also revealed a consistent application of fungicides. Chlorothalonil, a broad-spectrum fungicide, was detected in all three samples, indicating its widespread use for managing fungal diseases in guava orchards (Imran-ul-Haq et al., 2013). Similarly, captan was found in all locations, and its presence, alongside chlorothalonil, suggests significant efforts to control both field and post-harvest fungal infections. Beyond these, the pesticide load was further complicated by the presence of other specific compounds, particularly in the Al-Hadrah sample. These included acetamiprid, a neonicotinoid insecticide, and triazophos, another organophosphate. The detection of these diverse pesticides underscores the complex and multi-faceted pest management strategies employed, which consequently lead to a correspondingly complex mixture of chemical residues on the fruit (Huded et al., 2023).

Notable contaminants and regulated compounds

Several non-insecticidal compounds of regulatory and toxicological concern were also identified. Maleic hydrazide, a plant growth regulator, was detected in all three samples. Its use is often strictly regulated due to concerns about its potential carcinogenicity, as highlighted in risk assessments by the European Food Safety Authority (AEFS 2018). A finding of particular concern was the identification of dibutyl phthalate, which is not a pesticide but a plasticizer. Its high concentration in Fuwwah (18.97%) and its presence in Rosetta suggest significant contamination, potentially originating from plastic packaging materials, irrigation systems, or general environmental pollution. Dibutyl phthalate is a known endocrine disruptor and poses significant health risks, including effects on reproductive development (Heudorf et al., 2007). Finally, the dinitroaniline herbicide pendimethalin was found in all locations, confirming its routine use for weed control in these guava cultivation systems.

Implications for food safety and regulatory compliance

The findings from the GC-MS analysis of guava fruits from three major Egyptian governorates present a multifaceted challenge with serious implications for food safety, regulatory compliance, and public health. The detection of 24 distinct chemical compounds, with significant regional variation in both the number and concentration of residues, points to widespread and potentially unregulated pesticide use that demands immediate attention. The most direct implication of this study is the potential risk to consumer health. The presence of multiple pesticide residues, a phenomenon known as the "cocktail effect," is a primary concern. Traditional risk assessments and the establishment of MRLs are predominantly based on the toxicity of individual compounds. However, the simultaneous presence of multiple pesticides with similar mechanisms of action, particularly the acetylcholinesterase-inhibiting organophosphates (e.g., diazinon, dimethoate, malathion) and carbamates (e.g., carbofuran, promecarb), can lead to additive or even synergistic toxic effects (Kortenkamp 2014; Kortenkamp et al., 2009). This means that even if individual residues are below their specific MRLs, their combined action could pose a significant toxicological threat, potentially leading to acute symptoms or chronic health issues. Furthermore, the high relative percentages of certain compounds are alarming. The dominance of synthetic pyrethroids like lambda-cyhalothrin (up to 41.87%) and deltamethrin, while less acutely toxic than organophosphates, raises flags for chronic exposure. Studies have linked long-term exposure to pyrethroids to neurotoxic effects, including developmental neurotoxicity (Shafer et al., 2005). The detection of specific, highly toxic compounds such as carbofuran, a carbamate with high acute toxicity that is banned or heavily restricted in many countries, is particularly troubling and indicates a critical failure in the supply chain or farmer education.

Beyond pesticides, the identification of dibutyl phthalate, a plasticizer and known endocrine disruptor, introduces a non-agricultural chemical hazard into the food chain. Its presence, especially at a high concentration of 18.97% in Fuwwah, suggests post-harvest contamination from plastic packaging, liners, or polluted irrigation water. Endocrine disruptors like dibutyl phthalate can interfere with hormonal function at very low doses and are associated with adverse reproductive and developmental outcomes (Czubacka et al., 2021). Similarly, the consistent detection of maleic hydrazide, a plant growth regulator with potential carcinogenic concerns (AEFS 2018), adds another layer of chronic health risk. These findings significantly broaden the scope of food safety concerns from purely agricultural pesticides to include industrial and post-harvest contaminants.

From a regulatory standpoint, the results suggest a likely non-compliance with national and international MRLs. The extreme concentrations of pyrethroids and the presence of restricted-use compounds like carbofuran strongly indicate that the established safety thresholds are being exceeded. The regional variation in pesticide profiles, with Al-Hadrah showing the most complex contamination, highlights disparities in local agricultural practices and enforcement. This variation could stem from differences in local pest pressures, the availability of specific pesticides, or the level of training and oversight provided to farmers (Bottrell and Schoenly 2018). The prevalent use of pesticide mixtures, as seen in Al-Hadrah with its cocktail of pyrethroids, organophosphates, and neonicotinoids, suggests practices aimed at overcoming pest resistance or managing multiple pests simultaneously. However, this approach, if not guided by IPM principles, leads to a dangerous accumulation of residues and accelerates the development of resistance, creating a vicious cycle of increasing pesticide use (Singh et al., 2023). The detection of fungicides like chlorothalonil and captan in all samples confirms their routine use, but their co-occurrence with insecticides underscores the complete reliance on chemical solutions for crop protection. The presence of dibutyl phthalate also points to a regulatory gap in monitoring non-pesticide contaminants in fresh produce, emphasizing the need for a more holistic food safety framework that covers the entire supply chain from farm to fork.

Conclusion

This study provides a comprehensive and concerning profile of pesticide residues and contaminants in guava fruits cultivated in three major Egyptian governorates. The GC-MS analysis unequivocally demonstrates a widespread and complex pattern of chemical contamination, with a total of 24 distinct compounds identified. The significant regional variation in both the number and concentration of residues, with Al-Hadrah exhibiting the most complex profile, underscores pronounced differences in local agricultural practices, pest management strategies, and likely, the efficacy of regulatory oversight. The most striking finding is the heavy and dominant reliance on synthetic pyrethroids, particularly lambda-cyhalothrin and deltamethrin, which constituted the most abundant residues across all locations. While valued for their efficacy, their high concentrations raise immediate concerns regarding compliance with MRLs and the potential for chronic neurotoxic effects in consumers. Furthermore, the detection of multiple acetylcholinesterase inhibitors, including organophosphates like diazinon and malathion and carbamates like carbofuran, presents a significant risk of additive toxicity. The "cocktail effect" from this mixture of compounds with similar mechanisms of action means that the cumulative risk to consumers is likely much greater than the risk posed by any single residue, challenging the current MRL-based regulatory framework. Beyond conventional pesticides, the identification of toxicologically significant non-insecticidal chemicals broadens the scope of food safety concerns. The consistent presence of the plant growth regulator maleic hydrazide, with its potential carcinogenicity, and the high concentration of the endocrine-disrupting plasticizer dibutyl phthalate indicate contamination sources extending beyond the field into post-harvest handling and packaging, highlighting critical gaps in the current monitoring regime. Overall, these findings signal an urgent need for a multi-faceted response. This includes strengthening regulatory enforcement and monitoring programs to ensure MRL compliance, promoting the adoption of IPM strategies to reduce reliance on chemical pesticides, and providing farmer education on the safe and judicious use of agrochemicals. Future research should focus on quantitative risk assessment of the detected chemical mixtures and expand monitoring to cover a wider range of potential contaminants throughout the entire food supply chain to ensure the safety of guava and other fresh produce for the consumer.

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, upon reasonable request.

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فحص بقايا المبيدات المتعددة من مناطق جغرافية مختلفة في مصر: دراسة حالة لفاكهة الجوافة

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بحثت هذه الدراسة في خصائص وتباين بقايا المبيدات والملوثات على مستوى المناطق في فاكهة الجوافة المزروعة في ثلاث محافظات مصرية رئيسية: الحضرة (الإسكندرية)، ورشيد (البحيرة)، وفوة (كفر الشيخ) .باستخدام تحليل كروماتوغرافي الغاز-مطياف الكتلة-GC) (MS، تم تحديد مجموعه من 24 مركبًا كيميائيًا مميزًا، مما كشف عن تلوث كبير وممارسات زراعية متنوعة في جميع المناطق. أظهرت عينات منطقة الحضرة بالأسكندرية التركيب الأكثر تعقيدًا بـ 18 مركبًا، تليها منطقة رشيد بالبحيرة (13) ثم منطقة فوّه بكفر الشيخ (11 مركب). وكانت البيرثرويدات الاصطناعية، وخاصةً لامدا-سيهالوثرين (المركب الأكثر وفرة في منطقتين، بنسبة تصل إلى 41.87%) ودلتاميثرين، هي السائدة بشكل كبير .كما كشف التحليل عن مستويات مثيرة للقلق من الفوسفات العضوية (مثل الديازينون، والديميثوات، والملاثيون) والكاربامات (مثل الكاربوفوران)، والتي يزيد تواجدها المتزامن من خطر الآثار السامة المضافة .علاوة على ذلك، تم الكشف باستمرار عن مبيدات الفطريات (الكلوروثالونيل، والكابتان) ومنظم نمو النبات هيدرازيد الماليك .كان من النتائج المهمة تحديد مادة فثالات ثنائي البوتيل الملدنة بتركيزات عالية (تصل إلى 18.97%)، مما يشير إلى احتمال تلوثها بعد الحصاد أو تلوثها البيئي .وتُبرز النتائج تداعيات خطيرة على سلامة الأغذية والامتثال للأنظمة .وتشير مستويات المخلفات العالية، ووجود مركبات شديدة السمية مثل الكاربوفيوران، والمزيج المعقد من المبيدات الحشرية ذات طرق العمل المتشابهة، إلى احتمال تجاوز الحدود القصوى للمخلفات (MRLs)، وتُشكل مخاطر صحية محتملة نتيجة التعرض الحاد والمزمن .وخلصت الدراسة إلى أن الاستخدام المكثف للمبيدات الحشرية في الجوافة المصرية يُنتج مزيجًا من المخلفات الخطرة، مما يتطلب تشديد الرقابة، وتوعية المزارعين بممارسات أكثر أمانًا، وتوسيع نطاق مراقبة سلامة الأغذية.