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Pesticide residues in non-primary edible plant parts: Regulatory considerations and dietary risk assessment of guava leaves

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ABSTRACT

Rising consumption of non-primary edible plant parts is creating previously underaddressed pesticide residue and dietary exposure concerns. Guava leaves are widely consumed as herbal infusions and incorporated into pharmaceutical and food products. However, intensive pesticide use during cultivation may result in residue accumulation in leaves and derived products, raising potential public health concerns. This study investigated the occurrence and levels of multi-class pesticide residues in eleven dried guava leaf samples (branded and non-branded) and four guava-containing pharmaceutical preparations collected from Egypt. Compliance with European Union Maximum Residue Limits (EU-MRLs) and realistic consumer exposure scenarios were evaluated. Additionally, a leaf sample was traced back to its farm source, where associated environmental matrices (soil and irrigation water) and guava fruit were analyzed to assess pesticide contamination. Detected concentrations ranged from 0.0015 mg/kg (lufenuron) to 1.97 mg/kg (imidacloprid), with 8–27 residues per sample. Environmental samples showed minimal contamination, and the corresponding fruit contained only one residue. Infusion processing factors refined exposure estimates. Dietary risk assessment based on Estimated Daily Intake and risk quotient calculations for adults, children, and infants indicated no appreciable health risk, despite the high frequency of pesticide occurrence.

1. Introduction

Globally, there is growing interest in non-primary edible plant parts, such as the leaves of major crops, driven by their high content of bioactive compounds(Singh et al., 2023). Guava (*Psidium guajava*) leaves, for instance, are increasingly used in herbal teas, pharmaceutical preparations, dietary supplements and food industry due to their antimicrobial, anti-inflammatory, and antioxidant properties.(Kumar et al., 2021). Also, guava leaves have been reported to be effective in extending the shelf life of meat due to its antimicrobial activities against foodborne pathogens (Ann et al., 2022). However, guava cultivation is highly susceptible to insect infestation, pests, and microbial diseases, which forces farmers to rely extensively on chemical pesticides to protect crop yield and improve productivity(Malhat et al., 2026).

The misuse of such chemicals such as Plant Protection Products (PPPs) may lead to the accumulation of hazardous residues in plant tissues, which subsequently enter the food chain and pose serious risks to human health and environmental sustainability(Acharya et al., 2025). Pesticide residues can remain on the crops, even when the pesticides are applied in accordance with Good Agriculture Practices (GAP) (Machado et al., 2017).

Several studies have previously reported the dietary exposure to pesticide residues through the consumption of fruits, vegetables and several aromatic plants collected from Egyptian markets(Fathelbab Eldawlatly et al., 2025; Gad Alla et al., 2015a; Malhat et al., 2025; Refaat et al., 2025). Furthermore, a recent large-scale study conducted on guava samples from Egyptian markets revealed that a considerable proportion of the detected residues exceeded the established MRLs, raising some public health concerns(Malhat et al., 2026). Nonetheless, there hasn't been a study that focused on the presence of pesticides in Egyptian guava leaves till the best of our knowledge.

Reference bodies such as the Codex Alimentarius Commission ("Maximum Residue Limits | CODEXALIMENTARIUS FAO-WHO," n.d.) and the European Union (EU)(European Commission, 2024) set Maximum Residue Limits (MRLs) to monitor pesticide residues in food to ensure consumer safety.

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Pesticide transfer kinetics describes the rate and extent to which pesticide residues migrate from plant material into the prepared infusion during brewing. Recent studies have demonstrated that pesticide transfer is primarily governed by the physicochemical properties of the pesticide, for example, the octanol–water partition coefficient (log P) and aqueous solubility. Highly polar pesticides with low log P values and high solubility exhibit high transfer rates, whereas non-polar pesticides with high log P values show limited transfer into the infusion(Chen et al., 2017). In addition, compound volatility can play a key role in pesticide transfer kinetics during infusion and thermal processing, as more volatile compounds may partially dissipate during brewing or boiling processes(Gupta and Shanker, 2009). Current studies on pesticide residues in herbal medicines infusions (for example guava leaves) suffer from limited studies on the establishment of transfer kinetics of pesticides from plant materials into the prepared beverage, in comparison with more popular beverages such as tea(Hu et al., 2026; Wang et al., 2019; Xiao et al., 2017). This is an important step to establish a realistic risk assessment process(Gamal et al., 2025).

Hence, this study aimed to quantitatively determine multi-residue PPPs in guava leaves collected from different cities and multiple agricultural sources within the Egyptian local market using the Quick, Easy, Cheap, Effective, Rugged and Safe (QuEChERS) sample preparation method in combination with liquid chromatography coupled to tandem mass spectrometry (LC-MS/MS). Furthermore, the transfer kinetics of the detected pesticides into guava leaf infusions was investigated to provide a realistic human exposure assessment. In addition, selected guava samples were traced back to their farming sources, where corresponding soil and water samples were collected and analyzed to assess possible environmental contamination routes. The impact on the presence of pesticide residues in pharmaceuticals that contains guava and guava leaves was also investigated with a focus on children's medicine.

2. Materials and methods

2.1. Chemicals and reagents

All organic solvents, i.e. methanol, acetonitrile (HPLC grade) and toluene (≥99.9%) were purchased from Merck (Germany). Formic acid, 98–100%, and ammonia solution, 33%, were procured from Riedel–de Haen (Germany). Millipore water-purification system (Millipore, USA) was used for ultra-purified water generation. Agilent technologies (USA) supplied QuEChERS extraction reagents that contained magnesium sulphate, sodium chloride, sodium citrate and citric acid disodium salt mixed in one package. Pesticide reference standards of >95% purity were purchased from Dr. Ehrensdorfer (Germany).

2.2. Pesticides standard preparation

Stock standard solutions (1000 μg/ml) for all tested pesticides were prepared individually in toluene. Spiking solution of 5 μg/ml from all pesticides were prepared by collecting and diluting stock solution in methanol. Calibration solution mixtures were prepared in six concentration levels 0.001, 0.002, 0.005, 0.01, 0.05 and 0.1 μg/ml in methanol. Stock solutions were kept at −20 ± 2°C. Intermediate and calibration solutions were stored at 4 ± 2°C. Standard-in-matrix solutions were prepared freshly to compensate for possible signal suppression, as described previously(Emad R. Attallah et al., 2017), for each commodity by diluting an exact amount of the composite standard solution in matrix extract.

2.3. Sample extraction

The extraction method was based on the citrate-buffered QuEChERS approach(Payá et al., 2007), with modifications to accommodate the dry nature of the analyzed herbal samples, as previously described for multiresidue pesticide analysis in dry herbs using LC–ESI–MS/MS(Taha and Gadalla, 2017). For the guava and medicine samples 10 g were weighed into 50 mL polypropylene tubes. For the guava leaves and soil samples 2 g were weighed followed by the addition of 10 mL deionized water. This mixture was mixed with vortex (5 s) and left for 10 min for sample hydration. Ten mL of acetonitrile was added and mixed with sample and mixed by vigorously shaking for 1 min. Then buffer–salt mixture was added, and the sample was shaken again for 1 min. Centrifugation was carried out for 5 min at 4000 rpm, and the filtration of an aliquot was done by 0.45 μm syringe filter before LC-MS/MS injection. Water samples were centrifuged for 5 min at 4000 rpm, and filtered using 0.45 μm syringe filter for LC-MS/MS analysis.

2.4. LC-MS/MS analysis

LC-MS/MS analysis was conducted utilising a Shimadzu high-performance liquid chromatography (HPLC) system (Exion LC) coupled with an API 6500+ QTRAP mass spectrometer manufactured by (AB SCIEX). Soft electrospray ionisation (ESI) was utilized as the ionisation mode for the analysis of pesticides. Chromatographic separation was performed employing an Agilent Poroshell 120 C18 solvent-saver LC column (3 mm × 50 mm × 2.7 μm). The mobile phase consisted of solvent (A), comprising a mixture of Milli-Q water and methanol in a ratio of 9:1 (v:v), adjusted to pH 4, and solvent (B), consisting solely of methanol. The examination of the designated pesticides was conducted during a 16-min runtime, with the mobile phase flowing at a rate of 0.3 mL/min, as per the solvent gradient programme outlined in Table 1 The mobile phase gradient programme and instrumental parameters were applied as previously described for multi-class pesticide residue analysis using LC–MS/MS.(Mamdouh et al., 2024).

The temperature of the thermostatic column oven was set to 40°C, and the injection volume was standardised to 2.0 μL. Electrospray ionisation (ESI) functioned in positive mode, with the following parameters: source temperature (TEM) maintained at 450°C, ion spray voltage (IS) set at 5500 V, collision gas (CAD) optimised to medium, curtain gas pressure (CUR) maintained at 25 psi, atomising air pressure set to 45 psi, auxiliary gas pressure adjusted to 45 psi, and the input potential calibrated to 10 V. A Multiple Reaction Monitoring (MRM) parameters for the compounds were as described in Multiple Reaction Monitoring (MRM) parameters for the investigated compounds were applied as previously described in validated multiresidue LC–ESI–MS/MS methods for dry matrices(Emad R Attallah et al., 2017; Elshabrawy et al., 2021). The method acquisition, instrument control, and data processing were facilitated by Analyst version 1.6.3 software.

2.5. Quality control

Quality control measures were strictly implemented to ensure the accuracy and precision of the analytical method. Reagent blanks and matrix blank samples were systematically analyzed with each batch to confirm the absence of contamination and target interferences. Matrix-matched calibration curves were utilized for quantification to compensate for matrix effects, with method linearity verified based on the back-calculated concentrations of the calibration standards deviating by no more than ±20% from their nominal values. For every sample batch, spiked quality control samples were prepared at 0.05 mg/kg and

Table 1
Mobile phase gradient program.

Total time (min)	Flow rate (mL/min)	A (%)	B (%)
0.0	0.3	60	40
1.0	0.3	60	40
11.5	0.3	10	90
12.0	0.3	0	100
13.0	0.3	0	100
14.0	0.3	60	40
16.0	0.3	60	40

analyzed alongside the samples to verify method performance. The criteria for acceptable performance included recoveries within the range of 70–120% in accordance with the European Commission guidance document on Analytical Quality Control and Method Validation Procedures for Pesticide Residues Analysis in Food and Feed (SANTE/11312/2021 v2026) (Elmahdy et al., 2026).

2.6. Sample collection

Dried guava leaf samples intended for infusion preparation were collected from Egyptian local markets over three months period. Due to the limited availability and relative rarity of these specialized products in the market, a total of 10 samples were obtained from herbal shops, pharmacies, and open markets located in different governorates including Cairo, Giza, and El monofia.

In addition, 1 guava leaf sample was collected directly from its corresponding cultivation sites, in addition to a water, soil and guava sample from the same farming land. From each selected cultivation site, associated soil and irrigation water samples were also collected to investigate potential environmental contamination pathways. All samples were transported to the laboratory in clean polyethylene containers, properly labeled, until extraction and instrumental analysis. Furthermore, four guava leaf–based pharmaceutical products intended for pediatric use were acquired.

2.7. Processing factor

Processing factors (PFs) were calculated to evaluate the effect of infusion preparation on the transfer behaviour of pesticide residues from dried guava leaves into the aqueous phase. For each detected pesticide, the PF was calculated as the ratio between the concentration measured in the prepared guava leaf infusion that was left to sit for 10 min with boiling water and the concentration determined in the corresponding dried leaf sample, according to the following equation:

$$PF = C\_inf / (C\_leaf \times \rho\ water) \quad (1)$$

where C_inf (mg/L) is the concentration of the pesticide in the infusion C_leaf (mg/kg) is its concentration in the dried guava leaves and **ρ water is the water density expressed as 1 kg/L**.

A PF < 1 indicates that filtrate residue concentrations are lower than those in the dry leaves, decreasing consumer exposure. Conversely, PF > 1 signifies enhanced transfer into the infusion(Yigit and Velioglu, 2020). The calculated PFs were used to support the dietary exposure assessment and to describe the transfer behaviour of individual pesticides during infusion preparation.

2.8. Deterministic dietary exposure

To estimate dietary exposure to pesticide residues through the consumption of guava leaf infusions, the Estimated Daily Intake (EDI) was calculated for each detected pesticide using a deterministic approach. The EDI was calculated based on the pesticide concentration in the dried leaves, the daily intake rate of the infusion, the corresponding processing factor, and the average body weight, as described by the following equation(Cámara et al., 2020):

$$EDI = (C \times IR \times PF) / BW \quad (2)$$

where C (mg/kg) is the mean concentration of the pesticide in dried guava leaves, IR (2 g/day) is the daily intake rate of guava leaf infusion (based on the food cluster diets data provided by the WHO using herbs as proxy) (WHO, 2026), PF is the processing factor calculated for each pesticide, and BW (kg) is the average body weight of the consumer, assumed to be 70 kg for adults, 15 kg for children, and 10 kg for infants. (Gad Alla et al., 2015a)

2.9. Risk assessment

The potential health risk associated with pesticide intake through guava leaf infusions was assessed by comparing the calculated EDI values with the corresponding Acceptable Daily Intake (ADI) values established by international regulatory authorities. The risk quotient (RQ) for each pesticide was calculated according to the following equation (Gad Alla et al., 2015a):

$$RQ = (EDI / ADI) \quad (3)$$

An RQ value lower than 1 indicates an acceptable level of risk for consumers, whereas RQ values equal to or exceeding 100% indicate a potential health concern. The obtained risk estimates were interpreted in relation to international food safety standards and previously published dietary exposure studies. Furthermore, the Hazard Index (HI) was calculated by summing all the RQ according to the following equation:

$$HI = \sum RQi \quad (4)$$

The calculation of HI provides a screening assessment of the cumulative toxicological effects of combined residue exposure, which reflects a more realistic consumer exposure scenario than evaluating individual compounds alone.

3. Results and discussion

3.1. Occurrence of pesticide residues in guava leaves

Multi-class pesticide residues were detected in all analyzed guava leaf samples collected from Egyptian local markets and cultivation sites. Detected concentrations varied widely (Table S1 in the supplementary data), ranging from trace levels close to the limit of quantification to a maximum concentration of 1.97 mg/kg (imidacloprid), this indicates several possibilities such as heterogeneous pesticide application practices.(Prodhan et al., 2024), or harvesting the crop without waiting for the recommended pre harvest interval (Eissa et al., 2024).

Because default European regulations set MRLs equal to the limit of quantification (LOQ) in the absence of a dedicated value, strict adherence to this rule would render all samples technically non-compliant. However, in case of guava leaves, compliance of the detected pesticides is usually evaluated against the generic EU MRL for herbal infusions which may not always be appropriate due to the difference in nature between each herbal infusion. To provide a more appropriate toxicological and practical evaluation, results were also compared against alternative MRLs from botanically relevant commodities (such as grape leaves and laura leaves) which share closer structural and matrix characteristics to guava leaves than generic herbal infusions (in addition to guava fruit itself). Fig. 1 illustrates the MRL compliance comparison using both the default LOQs and these alternative commodity thresholds.

Another limitation is that the MRLs are usually set by measuring the pre harvest interval (PHI) studies(EFSA, 2015). These studies are usually done on the primary edible crop itself(Malhat et al., 2022). This results in the MRL noncompliance of the majority of the non-primary edible plant parts.(“CVUA Stuttgart | Problemfall Weinblätter – …,” n.d.; Hamzawy, 2022)

It is also worth noting that branded samples (Sample 1-4), had less pesticide concentrations than non-branded samples. Indicating a better quality control/quality assurance process as observed before(Hari et al., 2024).

Lastly, a sample (sample 5) was traced to its farming source, and the irrigation water, soil, and guava from this agriculture site were analyzed. The water didn't show any pesticide residues, the soil had traces of cypermethrin (0.005 mg/kg), and the guava had also some traces of cyfluthrin (0.008 mg/kg). This indicates that the pesticides detected in the guava leaves are from direct foliar application(Juraske

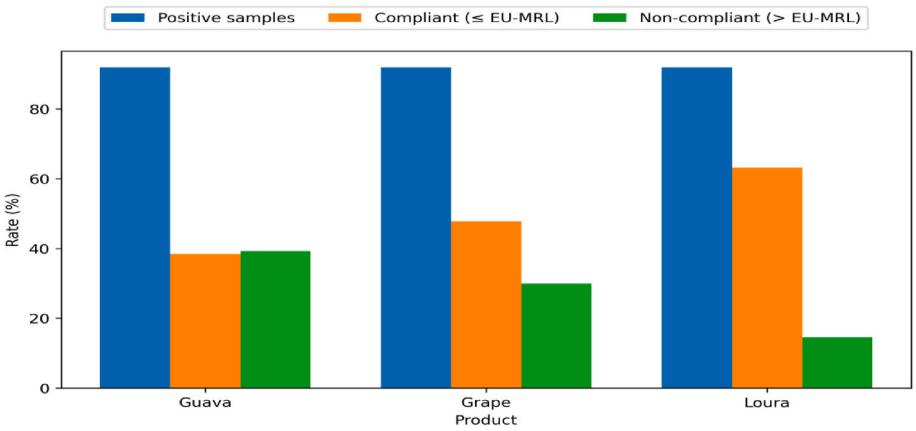

Fig. 1. Comparison of pesticide residue compliance in guava leaves based on EU-MRLs established for related commodities (guava fruits, grape leaves, and loura leaves). Samples containing at least one residue exceeding the applied MRL were classified as non-compliant.

et al., 2009), and that leafy parts are more susceptible to pesticides contamination(Ahmadi et al., 2024).

3.2. Pesticides classification

The detected pesticide residues belonged to several chemical classes, including pyrethroid insecticides, organophosphate insecticides, neonicotinoid insecticides, triazole fungicides, benzimidazole fungicides, in addition to other minor classes (Fig. 2).

Pyrethroid insecticides constituted the most prevalent chemical class, accounting for 20.41% of detected residues, followed by organophosphates (19.90%) and neonicotinoids (11.73%). Other pesticide classes collectively represented 34.70%, reflecting the diversity of compounds applied during guava cultivation.

Classification based on pesticide use revealed that insecticides were the dominant group, accounting for 61.61% of all detected residues (Fig. 3). Fungicides represented 17.54%, while acaricides, herbicides, and other compounds accounted for smaller proportions. The predominance of insecticides reflects the high pest pressure associated with guava cultivation and the reliance on chemical pest control strategies (Malhat et al., 2026).

Notably, the EU banned pesticide chlorpyrifos was present in 10/11 guava leaves samples. This may result in the hindrance of the crop trade due to EU MRLs noncompliance. In the last 3 years, there has been more

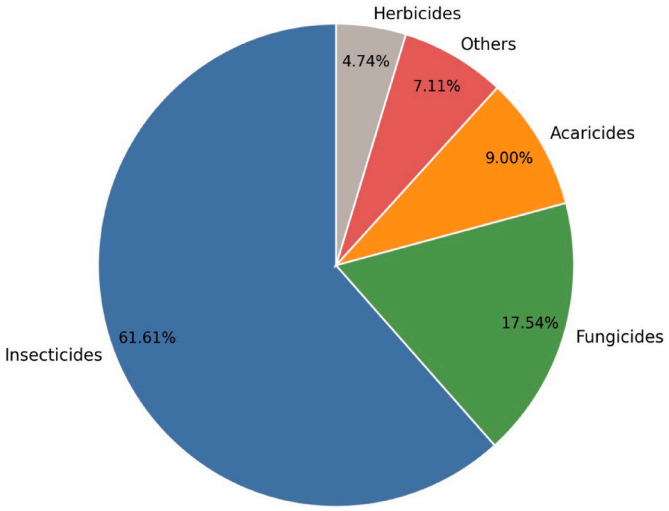

Fig. 3. Use-based classification of detected pesticide residues in guava leaves.

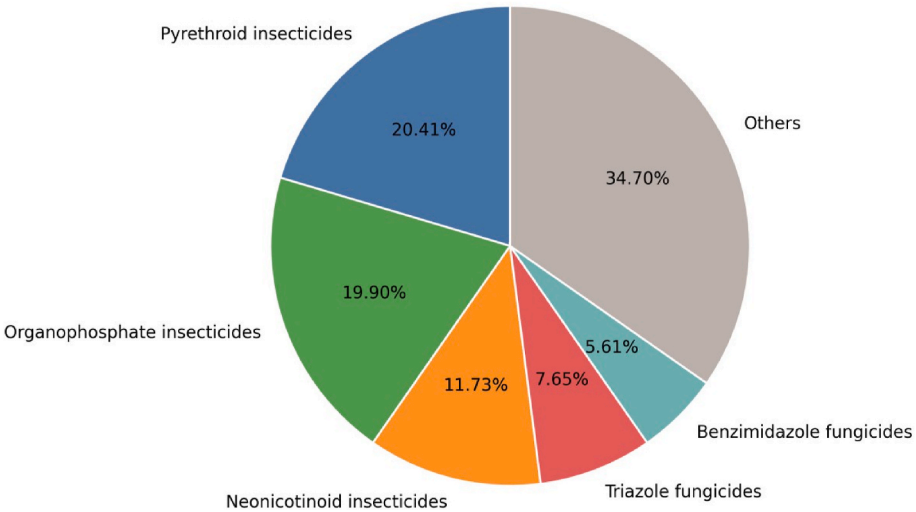

Fig. 2. Chemical class distribution of detected pesticide residues in dried guava leaves.

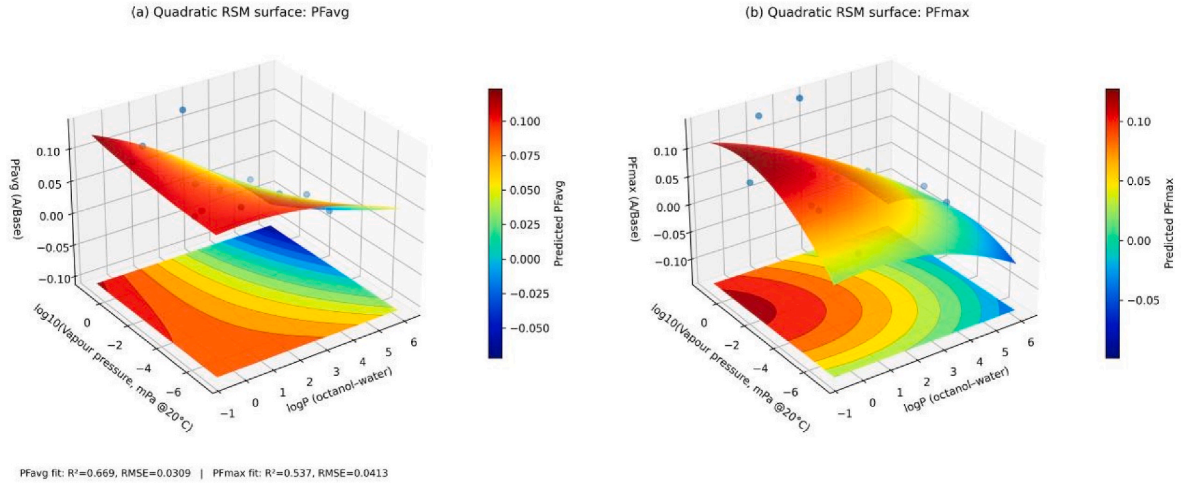

Fig. 4. Three-dimensional surface plots illustrating the relationship between experimental processing factors (PFavg and PFmax), log P (octanol–water partition coefficient), and vapor pressure.

than 10 cases of different commodities where an imported shipment from Egypt has been rejected due to the presence of chlorpyrifos. ("RASFF Window - Results," 2025)

3.3. Pesticides in pharmaceutical products

Multi-class pesticide residues were detected in four pharmaceutical products containing guava leaves. The number of detected residues varied between samples, reflecting differences in raw material quality and sourcing. Several residues detected in pharmaceutical products were identical to those detected in dried guava leaves, indicating that contamination originated mainly from the plant material rather than the manufacturing process (Table 2). In total, three samples showed positive results, with one to two pesticide residues detected per product.

3.4. Risk assessment

To get true estimates of consumed pesticides, PF was calculated using 3 samples (Sample 3, 6, and 7), as described in equation (1), to cover all the detected pesticides (Table 3) and to ensure that the PF results are representative of different guava leaves conditions such as grinding degree. As discussed in the introduction, pesticides transfer from the leaves to the infusion heavily depends on two factors log P (octanol–-water partition coefficient), and vapor pressure. Hence, three-dimensional surface models were constructed to describe the relationship between experimental processing factor (PF) values, log P, and vapor pressure. Assuming a constant relationship between C_inf and C_leaf, quadratic response surface methodology (RSM) models were built where it demonstrated reasonable predictive performance (PFavg: $R^2 = 0.669$; PFmax: $R^2 = 0.537$), enabling estimation of PF values for pesticides lacking experimental data (Fig. 4).

The EDI of each pesticide was estimated according to equation (2). The RQ of each pesticide was calculating by dividing the EDI by the ADI of each pesticide (equation (3)), and the HI indicates the sum of all the RQs. As shown in Tables 4 and 5, all the pesticides' RQs are far below 1

Table 2
Concentrations of pesticide residues detected in different pharmaceutical samples expressed as mg/kg.

Pesticide	Sample 1 (mg/kg)	Sample 2 (mg/kg)	Sample 3 (mg/kg)	Sample 4 (mg/kg)
Acetamiprid	0.0009	ND	ND	ND
Carbendazim	0.0014	ND	0.00036	ND
Imidacloprid	ND	0.0012	0.0014	ND

Table 3
Average and maximum pesticide concentrations in raw guava leaves and corresponding infusions, along with calculated processing factors (PFavg and PFmax).

Pesticide	Base avg	A avg	PFavg	Base max	A max	PFmax
Acetamiprid	0.136	0.006	0.044	0.186	0.01	0.054
Chlorpyrifos	0.142	0.0	0.002	0.199	0.0	0.002
Deltamethrin	0.026	0.0	0.018	0.041	0.0	0.012
Dimethoate	0.024	0.002	0.101	0.03	0.005	0.153
Fenitrothion	0.061	0.001	0.009	0.061	0.001	0.015
Malathion	0.009	0.0	0.015	0.012	0.0	0.017
Piperonyl butoxide	0.014	0.0	0.007	0.025	0.0	0.004
Carbendazim	0.021	0.003	0.167	0.033	0.006	0.197
Imidacloprid	0.671	0.077	0.115	1.972	0.077	0.039
Cyhalothrin L	0.891	0.001	0.001	1.094	0.001	0.001
Methomyl	0.123	0.011	0.093	0.233	0.013	0.055
Cypermethrin	0.279	0.001	0.003	0.33	0.001	0.002
Thiamethoxam	0.004	0.0	0.1	0.004	0.0	0.1

PFavg = Processing factor calculated from average concentrations.
PFmax = Processing factor calculated from maximum concentrations.
Base avg = Average pesticide concentration in dried guava leaves (mg/kg).
A avg = Average pesticide concentration in infusion (mg/L).
Base max = Maximum pesticide concentration in dried guava leaves (mg/kg).
A max = Maximum pesticide concentration in infusion (mg/L).

which indicates that the present pesticides concentrations are safe(Eissa et al., 2020). Furthermore, the HI for the adults varied for adults, children, and infants respectively according to body weight(Gad Alla et al., 2015a). However, all HI were under 1 even for worst case scenarios using the highest concentrations of each detected pesticide, even for infants.

It is important to acknowledge that the risk assessment was done based on the body weight per previous risk assessment studies in Egypt (Gad Alla et al., 2015a) and the results can differ if the harmonized EU body weights were used that suggest different weight for infants (5 kgs in comparison 10 kgs that was used in this study). Additionally, the risk assessment could also change if this was done for high end users which will be further studied in future research work.

Furthermore, it worth noting that the HI for adults (0.0365) is less than the HI of pesticides in tea (0.175) and more than the HI of pesticides in coffee (0.000072) that are locally consumed in Egypt per our previous studies (Elmahdy et al., 2026; Gamal et al., 2025). Also, the HI range in raw vegetables per previous studies was at 0.15 maximum for the most consumed vegetable commodities such as tomato, cucumber,

Table 4
RQ based on infusion concentrations.

Pesticide	RQavg (Adult)	RQmax (Adult)	RQavg (Child)	RQmax (Child)	RQavg (Infant)	RQmax (Infant)
Acetamiprid	0.0007	0.0011	0.0032	0.0053	0.0048	0.0080
Carbendazim	0.0004	0.0009	0.0016	0.0032	0.0024	0.0048
Chlorpyrifos	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Cypermethrin	0.0006	0.0006	0.0027	0.0027	0.0040	0.0040
Deltamethrin	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Dimethoate	0.0057	0.0143	0.0267	0.0667	0.0400	0.1000
Fenitrothion	0.0006	0.0006	0.0027	0.0027	0.0040	0.0040
Imidacloprid	0.0037	0.0037	0.0171	0.0171	0.0257	0.0257
Lambda-cyhalothrin	0.0006	0.0006	0.0027	0.0027	0.0040	0.0040
Malathion	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Methomyl	0.0126	0.0149	0.0587	0.0693	0.0880	0.1040
Piperonyl butoxide	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Thiamethoxam	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

RQ = Risk Quotient (%).
HI = Hazard Index.
RQ values were calculated according to Equation (3).
Total HI (sum of pesticides).

Table 5
RQ for pesticides detected in guava-containing pharmaceutical products (direct consumption; no processing factor applied). Mean (Cavg) and maximum (Cmax) concentrations were calculated excluding ND values. Risk was evaluated for children and infants under a conservative screening scenario.

Pesticide	Cavg (mg/kg)	Cmax (mg/kg)	RQavg (Child)	RQmax (Child)	RQavg (Infant)	RQmax (Infant)
Acetamiprid	0.00090	0.00090	0.000096	0.000096	0.000144	0.000144
Carbendazim	0.00088	0.00140	0.000094	0.000149	0.000141	0.000224
Imidacloprid	0.00130	0.00140	0.000058	0.000062	0.000087	0.000093

ND = Not detected.
RQ = Risk Quotient. RQ values were calculated according to Equation (3).
Cavg = Mean concentration excluding ND values.
Cmax = Maximum detected concentration.
Infant assessment is presented as a conservative theoretical screening, as some products are labeled for children older than two years.

and pepper (Gad Alla et al., 2015a). The sum of the those three HIs from different hot beverages and most consumed vegetable commodities is far from being a health concern as it is much less than 1.

4. Conclusion

This study reveals the widespread presence of multi-class pesticide residues in guava leaves marketed in Egypt, with many samples exceeding EU-MRLs when surrogate or default limits were applied. The predominance of insecticides, including the detection of the banned compound chlorpyrifos, underscores persistent shortcomings in pesticide management and regulatory compliance for medicinal plants.

Although residue levels were elevated in raw guava leaves, infusion preparation generally did not lead to concentrations in the infusion higher than in the leaves themselves, as extraction into the brew is often incomplete (with processing factors below unity) for most compounds. When these transfer characteristics were incorporated into dietary exposure assessment, hazard index values remained below one across all age groups, indicating a low health risk under realistic consumption conditions, though full exposure would still occur if the leaves themselves were consumed directly. This highlights the gap between the set MRLs and the actual risk for the consumer.

Overall, the findings highlight the need to account for preparation practices and realistic exposure pathways in residue evaluations of herbal products. The establishment of matrix-specific MRLs for herbal infusions, together with improved agricultural and post-harvest controls, would strengthen consumer protection and support international trade.

Lastly, it is recommended that more studies should be done on high end users to ensure the safety of similar products against misuse such as consumption without infusion.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author used Gemini AI for the help on the graphical abstract design. The author reviewed and edited the output as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Ganna Ashraf Ezzat: Investigation, Writing – original draft. **Mostafa Soliman:** Conceptualization, Investigation, Methodology, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.yrtph.2026.106191.

- Adult: **HIavg = 0.0248**, **HImax = 0.0365**
- Child: **HIavg = 0.1156**, **HImax = 0.1704**
- Infant: **HIavg = 0.1735**, **HImax = 0.2557**

Data availability

No data was used for the research described in the article.

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