

Pesticide residues and dietary health risks in onion marketed in Türkiye using deterministic and probabilistic approaches

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Research Article

Keywords: Allium cepa, pesticide residues, multi-residue occurrence, food safety, chronic risk, acute risk

Posted Date: October 19th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10965870/v1>

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Abstract

In this study, 120 onion samples from Türkiye were analysed for 222 pesticide residues using liquid chromatography-tandem mass spectrometry, and potential dietary risks were characterised using deterministic and probabilistic approaches. Quantifiable residues were detected in 38 onion samples (31.7%), while none of the detected residues exceeded the European Union maximum residue levels. Multiple residues occurred in 27 of the 38 positive samples (71.1%). Boscalid was the most frequently detected pesticide (28.3%). Under the upper-bound scenario, cumulative chronic hazard index (*Hlc*) values were 0.0028 for adults and 0.0035 for children. Probabilistic modelling supported the deterministic findings, with 95th percentile *Hlc* values of 0.00289 and 0.0035 for adults and children, respectively. Fluopyram and pyrimethanil were the principal contributors to probabilistic cumulative chronic risk, together accounting for approximately 80% of *Hlc*. Acute hazard quotient (*HQa*) values reached a maximum of 0.0408 in adults and 0.0910 in children. All chronic and acute risk estimates remained well below the threshold of concern, indicating a low dietary health risk for both adult and child consumers. The findings provide updated evidence on pesticide residue occurrence and dietary exposure associated with onion consumption in Türkiye and support the continued risk-based surveillance of this widely consumed commodity.

Introduction

Onion (*Allium cepa* L.) is one of the most widely cultivated and consumed vegetable crops worldwide, with global production exceeding 108 million tonnes annually (Akinwotu and Adeniran, 2025; FAO, 2026). Beyond its importance as a staple ingredient in diverse dietary patterns, onion is valued for its nutritional composition and abundance of bioactive constituents, particularly organosulfur and phenolic compounds, including flavonoids such as quercetin and its derivatives (Dorrigiv et al., 2021; Zhao et al., 2021; Elattar et al., 2024).

Onion production is challenged by numerous insect pests and diseases that can adversely affect crop yield and bulb quality. Onion thrips (*Thrips tabaci* Lindeman), one of the most economically important pests of onion worldwide, damages leaf tissues, reduces photosynthetic capacity, and, at high population densities, can substantially impair plant development and bulb yield (Gagnon et al., 2024). Fungal and bacterial diseases, including *Botrytis* leaf blight, *Stemphylium* leaf blight, downy mildew, and bacterial rots, can further reduce onion yield and quality (Constancio et al., 2023). Although cultural and biological management strategies are increasingly incorporated into crop protection programmes, pesticides continue to play an important role in controlling these biotic stresses and maintaining commercially acceptable yields. Their application, however, may result in pesticide residues remaining in or on harvested commodities, with residue levels influenced by factors such as application rate and frequency, pre-harvest interval, the physicochemical properties of the active substance, and environmental conditions (FAO, 2016).

The occurrence of pesticide residues in food has implications for both regulatory compliance and consumer safety. Dietary intake represents an important route of pesticide exposure for the general population, and the potential health implications depend on the toxicological characteristics of the active substance as well as the magnitude and duration of exposure (WHO, 2022; Shekhar et al., 2024). The detection of a pesticide residue in food does not necessarily indicate an unacceptable health risk, as its toxicological relevance depends on the level of dietary exposure. Dietary exposure should therefore be evaluated by considering residue concentrations and food consumption in relation to pesticide-specific health-based guidance values, particularly the acceptable daily intake (ADI) for long-term exposure and the acute reference dose (ARfD) for short-term exposure.

Maximum residue levels (MRLs) constitute a complementary regulatory tool for controlling pesticide residues in food. These limits are established on the basis of authorised uses under good agricultural practices, supported by supervised residue trials and dietary exposure considerations (EFSA, 2024). MRLs should not be interpreted as direct toxicological thresholds, but as regulatory benchmarks for assessing compliance with authorised pesticide uses while ensuring that consumer exposure remains at acceptable levels. Regular surveillance of marketed foods is therefore essential for identifying non-compliant products, characterising residue patterns, and generating occurrence data for dietary exposure assessment.

This need is particularly relevant for onion because of its widespread consumption and the range of pesticide applications that may be required during cultivation. Studies conducted in different geographical regions have reported a wide range of pesticide residues in onion, including the co-occurrence of multiple residues and concentrations exceeding established MRLs (Dakuyo et al., 2020; Loha et al., 2020; Gordan et al., 2025; Lučić and Onjia, 2025; Malhat et al., 2025; Ahimed et al., 2026). Despite the agricultural and dietary importance of onion in Türkiye, information on pesticide residues in this commodity remains scarce, with the available studies being limited and largely based on data generated several years ago (Bakırcı et al., 2014; Özcan, 2016). Updated data are therefore needed to characterise current residue patterns and provide a robust basis for evaluating consumer exposure.

The present study aimed to investigate pesticide residues in 120 onion samples collected in Türkiye, characterise their occurrence and concentration profiles, and evaluate compliance with the applicable MRLs. Potential dietary risks associated with onion consumption were assessed for adult and child consumers using deterministic approaches for both chronic and acute exposure, while chronic exposure was further characterised using probabilistic modelling to account for variability in residue concentrations and consumption patterns.

Materials and methods

Reagents, chemicals and standards

Analytical standards of the 222 target pesticides, each with a purity > 95%, were obtained from CPAchem (Sofia, Bulgaria), Sigma-Aldrich (Steinheim, Germany), and Dr. Ehrenstorfer GmbH (Augsburg, Germany). Individual primary stock solutions were prepared at 1000 mg/L in an appropriate solvent (water, methanol, acetonitrile, or acetone), depending on the polarity and solubility of each analyte. A mixed intermediate standard solution containing all target analytes at 10 µg/mL was prepared in acetonitrile and used for the preparation of matrix-matched calibration standards and the fortification of samples in recovery experiments. LC-MS-grade methanol and acetonitrile were purchased from Sigma-Aldrich (Steinheim, Germany), while analytical-grade glacial acetic acid (CH₃COOH, 100%), ammonium formate, and formic acid were obtained from Merck KGaA (Darmstadt, Germany). Ultrapure water was produced using a Milli-Q purification system (Millipore, Molsheim, France). Anhydrous magnesium sulfate and sodium acetate (CH₃COONa) were obtained from Carlo Erba Reagents (Val-de-Reuil, France), while primary-secondary amine (PSA) sorbent was purchased from Supelco (Bellefonte, PA, USA). PTFE membrane filters (0.22 µm) were supplied by Whatman (Clifton, NJ, USA).

Samples

A total of 120 onion samples, each representing a different batch, were collected during 2025 from supermarkets, local markets, and greengrocers located in the provinces of Corum, Amasya, Samsun, and Konya, Türkiye. Approximately 1 kg of onions was obtained for each sample and transported to the laboratory for analysis. Prior to homogenisation, the roots and any readily detachable parchment-like outer skin were removed, while the remaining whole commodity was analysed without washing. Each sample was thoroughly homogenised using a laboratory homogeniser (GM 300; Retsch, Haan, Germany) to obtain a representative test portion.

QuEChERS extraction procedure

QuEChERS extraction procedure

Pesticide residues were extracted using the quick, easy, cheap, effective, rugged, and safe (QuEChERS) procedure based on AOAC Official Method 2007.01 (Lehotay, 2007). The sample preparation and analytical workflow is illustrated in Fig. 1. Briefly, a 15 g portion of each homogenised onion sample was weighed into a centrifuge tube, followed by the addition of 15 mL of acetonitrile containing 1% (v/v) acetic acid. The mixture was shaken thoroughly, after which 6 g of anhydrous MgSO₄ and 1.5 g of CH₃COONa were added. The tube was shaken and centrifuged at 5000 rpm for 3 min. For dispersive solid-phase extraction (d-SPE) clean-up, a 2 mL aliquot of the upper acetonitrile layer was transferred to a tube containing 100 mg of PSA and 300 mg of anhydrous MgSO₄. After vortex mixing, the tube was centrifuged at 5000 rpm for 3 min. The resulting supernatant was filtered through a 0.22 µm PTFE membrane filter, transferred to an autosampler vial, and subjected to liquid chromatography-tandem mass spectrometry (LC-MS/MS) analysis.

LC-MS/MS analysis

The determination of 222 pesticide residues was performed using a Vanquish ultra-high-performance liquid chromatography (UHPLC) system coupled to a Q Exactive Focus Orbitrap high-resolution mass spectrometer (Thermo Fisher Scientific, Bremen, Germany). Chromatographic separation was achieved on an Accucore Vanquish C18 column (2.1 × 100 mm, 1.5 µm, Thermo Fisher Scientific) using gradient elution. Mobile phase A consisted of water-methanol (98:2, v/v) containing 0.1% formic acid and 5 mM ammonium formate, whereas mobile phase B consisted of methanol. The gradient programme was initiated at 80% A and 20% B, followed by a linear increase in mobile phase B to 70% within 1.5 min. This composition was maintained until 10 min, after which the initial mobile phase conditions were restored within 0.2 min and maintained for column re-equilibration until the end of the 13-min run. The flow rate was 0.6 mL/min, the column temperature was maintained at 40°C, and the injection volume was 10 µL.

Mass spectrometric detection was performed using a heated electrospray ionisation (HESI) source in multiple reaction monitoring (MRM) mode. The spray voltage was set at 2.8 kV, whereas the spray and vaporiser temperatures were maintained at 320 and 295°C, respectively. Instrument control, data acquisition, and data processing were carried out using TraceFinder software (version 5.1, Thermo Fisher Scientific). Identification and confirmation of pesticide residues were based on retention time, accurate mass measurements, and at least two diagnostic product ions in accordance with the SANTE/11312/2021 v2 guidance document (EC, 2021). The precursor and product ions used for the identification and quantification of all target pesticides are presented in Table S1.

The method was validated according to the performance criteria specified in the SANTE/11312/2021 v2 guidance document. Matrix-matched calibration was employed to compensate for matrix effects. Calibration curves were prepared at five concentration levels (0.005–0.25 mg/kg) using blank onion extracts fortified with the appropriate pesticide standards. All target analytes exhibited satisfactory linearity over the investigated concentration range, with coefficients of determination (R^2) greater than 0.99. The limit of quantification (LOQ) was established at 0.01 mg/kg for all pesticides. Recovery and precision results for the pesticides detected in the onion samples are presented in Fig. 2. Method trueness was evaluated at two fortification levels (0.010 and 0.050 mg/kg), each analysed in five replicates ($n = 5$). Mean recoveries across all target pesticides ranged from 75.7% to 113.8%, while those of the pesticides detected in the onion samples ranged from 89.5% to 105.1%. Method precision was assessed under repeatability (RSD_r) and within-laboratory reproducibility (RSD_{wR}) conditions, with values below 20% for all target pesticides. For the detected pesticides, RSD_r and RSD_{wR} values ranged from 2.28% to 16.68% and from 6.19% to 17.50%, respectively. All validation results complied with the acceptance criteria specified in the SANTE/11312/2021 v2 guidance document (acceptable recovery range: 70–120%; RSD_r and $RSD_{wR} \leq 20\%$).

Human health risk assessment

Pesticide risk ranking

A matrix-based scoring approach adapted from the framework developed by the UK Veterinary Residues Committee (Veterinary Residues Committee, 2007) was used to rank the pesticide residues detected in onion samples according to their relative risk. The overall risk score (S) was derived from six indices representing acute toxicity (A), toxicological potency (B), dietary contribution (C), application frequency (D), potential exposure of vulnerable population groups (E), and residue levels relative to the corresponding MRLs (F). Each index was scored according to the criteria specified in the original ranking matrix (Table S2), with the individual scores assigned to the detected pesticides presented in Table S3. The overall risk score was calculated using Eq. (1). Based on the calculated overall risk scores, pesticide residues were classified as high risk ($S \geq 20$), medium risk ($15 \leq S < 20$), or low risk ($S < 15$).

$$S = (A + B) \times (C + D + E) \times F$$

1

Indices A and B were assigned on the basis of median lethal dose (LD_{50}) values (WHO, 2020) and ADI values (EC, 2026), respectively. Dietary contribution (C) was determined using onion consumption data from the Turkish Statistical Institute (TUIK, 2026), while application frequency (D) reflected the frequency of pesticide application during the onion-growing period. In the absence of sufficient evidence to identify specific population groups with potentially elevated exposure, a default score of 3 was assigned to E . Residue level (F) reflected the distribution of measured residue concentrations relative to the MRLs.

For the calculation of D , the frequency of dosing (FOD) was expressed as the number of pesticide applications (N) relative to the duration of the onion-growing period (P , days), as shown in Eq. (2).

$$FOD = \frac{N}{P} \times 100$$

2

The residue occurrence score (F) was determined from the distribution of measured residue concentrations relative to the corresponding MRLs using Eq. (3).

$$F = \frac{(F_0 \times 1) + (F_1 \times 2) + (F_2 \times 3) + (F_3 \times 4)}{n}$$

where F_0 represents the number of samples without detectable pesticide residues, F_1 corresponds to samples containing residues below the MRL, F_2 denotes samples with residue concentrations between ≥ 1 and 10 times the MRL, F_3 represents samples exceeding ≥ 10 times the MRL, and n is the total number of analysed samples.

Deterministic dietary risk assessment

Chronic dietary exposure to each detected pesticide was estimated for adults and children aged 3–10 years using the national estimated daily intake (NEDI), and the corresponding chronic hazard quotient (HQ_c) was calculated according to Eqs. (4) and (5), respectively.

$$NEDI = \frac{\text{Concentration of residue (mg/kg)} \times \text{onion consumption (kg)}}{\text{Body weight (kg)}}$$

4

$$HQ_c = \frac{\text{Exposure of the concerned pesticide}}{\text{Reference value (ADI)}}$$

5

The mean daily per capita consumption of onion was 0.073 kg for adults (TUIK, 2026). Daily consumption for children was estimated as 40% of the adult value based on the age-specific adjustment recommended by USEPA (2018). Body weights of 70 kg for adults and 23 kg for children were used in the exposure calculations (EFSA, 2012). Concentrations below the LOQ were treated using a substitution approach to account for uncertainty associated with left-censored data (EFSA, 2010). For the lower-bound (LB), middle-bound (MB), and upper-bound (UB) scenarios, results below the LOQ were assigned values of zero, LOQ/2, and the LOQ, respectively.

Acute dietary exposure was estimated using the international estimated short-term intake (IESTI), and the corresponding acute hazard quotient (HQ_a) was calculated according to Eqs. (6) and (7), respectively. IESTI calculations were performed using Case 2b, as defined by WHO/FAO (2014), because the large portion (LP) consumption was lower than the unit weight of the edible portion (U_e).

Case

b: $LP < U_e$

$$IESTI = \frac{LP \times HR \times v}{bw}$$

6

$$HQ_a = \frac{IESTI}{ARfD}$$

7

The unit weight of the edible portion (U_e) for onion was 0.244 kg, and the highest residue (HR , mg/kg) corresponded to the highest concentration measured among the analysed samples. A variability factor (v) of 3 was applied, while LP values of 0.153 and 0.102 kg were used for adults and children, respectively (WHO, 2021). ARfD values for individual pesticides were obtained from the European Union (EU) pesticides database (EC, 2026). Where an ARfD was unavailable, the corresponding ADI was used as a conservative surrogate threshold for acute exposure assessment, consistent with the approach adopted by EFSA in its annual pesticide residue monitoring reports (EFSA, 2023).

Cumulative chronic and acute risks were expressed as the chronic hazard index (HIC) and acute hazard index (HIA), respectively, and calculated by summing the corresponding individual HQ s according to Eq. (8).

$$\text{Hazard Index (HI)} = \sum HQ$$

HQc, *HQa*, *Hlc*, and *Hla* values ≤ 1 were considered to indicate a low likelihood of health concern, whereas values > 1 were considered to indicate a potential health concern.

Probabilistic risk assessment

A two-dimensional Monte Carlo simulation (2D MCS) was performed to account for variability and uncertainty in chronic dietary exposure. Probabilistic risk assessment was conducted using OnVeMCS v1.1 (Onjia and Vesković, 2026). The food consumer scenario was applied, with adult and child consumers evaluated separately. UB concentration data from the 120 onion samples were used as inputs, with results below the LOQ assigned the corresponding LOQ value. Pesticide concentration data were modelled using lognormal probability distributions. The simulation comprised 10,000 iterations for variability and 100 iterations for uncertainty. Cumulative chronic risk was expressed as the *Hlc*, with the resulting distribution summarised by the 5th, 50th, and 95th percentiles (P5, P50, and P95, respectively).

Results and discussion

Occurrence and distribution of pesticide residues in onion

Of the 120 onion samples analysed for 222 pesticide residues, 38 (31.7%) contained at least one pesticide at a quantifiable concentration, while no quantifiable residues were detected in the remaining 82 samples (68.3%). Five pesticides, boscalid, ametoctradin, fluopyram, pyrimethanil, and fluopicolide, were detected at quantifiable concentrations, with their concentration distributions among positive samples shown in Fig. 3. None of the detected residues exceeded the EU MRLs. Detailed data on detection frequencies, residue concentrations, and MRL compliance are provided in Table S4. Among the positive samples, 11 (28.9%) contained a single residue and 27 (71.1%) contained multiple residues. Of the 27 multi-residue samples, 12 contained two residues, seven contained three, five contained four, and three contained five residues (Fig. 4).

Boscalid was the most frequently detected pesticide, occurring in 28.3% of the samples at concentrations ranging from 0.015 to 0.195 mg/kg, with a mean concentration of 0.050 mg/kg. Ametoctradin and fluopyram were each detected in 15.8% of the samples, with concentrations ranging from 0.014 to 0.127 and 0.012 to 0.062 mg/kg, respectively. Pyrimethanil occurred in 10% of the samples, whereas fluopicolide was the least frequently detected fungicide (5.8%). Although pyrimethanil occurred less frequently than ametoctradin and fluopyram, its mean concentration (0.035 mg/kg) exceeded those of both compounds, indicating that detection frequency alone did not reflect the magnitude of residue levels among positive samples.

As summarised in Table 1, the detection frequency observed in the present study (31.7%) was close to the 32% previously reported for onion samples from the Aegean region of Türkiye (Bakırcı et al., 2014) and was comparable to frequencies reported in Serbia (25%) (Lučić and Onjia, 2025), Egypt (30.2%) (Malhat et al., 2025), and Iran (35%) (Gordan et al., 2025). Considerably higher frequencies have been reported in Saudi Arabia (75%) (Ramadan et al., 2020) and Tanzania (58.3%) (Mahugija et al., 2017), while lower frequencies were observed in the EU (7.8%) (EFSA, 2019) and Brazil (11.7%) (Jardim and Caldas, 2024). Residues have also been detected in all onion samples analysed in studies from Egypt (Mahmoud et al., 2026) and Ethiopia (Loha et al., 2020). These differences should be interpreted with caution, as residue prevalence may be influenced by geographical and temporal variation in pesticide use, climatic and seasonal conditions affecting pest and disease pressure, sampling design, analytical scope and sensitivity, and the regulatory status of individual active substances. Despite the occurrence of residues in nearly one-third of the samples in the present study, no MRL exceedances were identified, whereas previous investigations have reported varying levels of non-compliance, including an earlier study from Türkiye in which 3% of onion samples exceeded the MRLs (Bakırcı et al., 2014).

The residue composition also differed markedly from those reported in previous studies. Predominant residues identified in onions across different geographical settings have included phenthoate, methomyl, p,p'-DDD, fluopyram, tebuconazole, pendimethalin, carbendazim, and azoxystrobin (Bakırcı et al., 2014; Mahugija et al., 2017; EFSA, 2019; Ramadan et al., 2020; Gordan et al., 2025; Malhat et al., 2025; Mahmoud et al., 2026). In contrast, the residue profile observed in the present study was dominated by fungicides, with boscalid showing the highest occurrence frequency. This pattern may reflect fungicide use for the management of economically important fungal and oomycete diseases of onion, including *Botrytis* leaf blight, purple blotch, *Stemphylium* leaf blight, and downy mildew (Hay et al., 2019; Hay et al., 2021; Steentjes et al., 2021; Stricker et al., 2021). Differences in residue composition among studies

may reflect regional plant protection practices, pesticide authorisations and use patterns, sampling periods, and differences in analytical scope.

Human health risk assessment

Risk ranking

All five pesticides detected in the onion samples were classified within the low-risk category according to the applied risk-ranking framework. Risk scores ranged from 9.01 to 11.64, with boscalid receiving the highest score (11.64), followed by ametoctradin and fluopyram (10.18 each), pyrimethanil (9.50), and fluopicolide (9.01). Despite receiving the highest score, boscalid remained below the threshold for the medium-risk category. Boscalid was also the most frequently detected pesticide (28.3%), although its risk score remained below the threshold for the medium-risk category. These findings differ from those reported by Lučić and Onjia (2025), who applied a comparable risk-ranking approach to pesticides detected in root and tuber vegetables and onions in Serbia and identified five active substances (chlorpyrifos, ethoxyquin, fosthiazate, isoprocarb, and metolachlor) within the high-risk category. This difference may reflect variation in the pesticides detected, their toxicological profiles, residue occurrence and concentration levels, consumption patterns, and pesticide-use practices across the two studies.

Dietary exposure and risk characterisation

For adults, chronic dietary exposure to individual pesticides ranged from 1.0×10^{-6} to 1.5×10^{-5} mg/kg bw/ day under the LB scenario and from 1.1×10^{-5} to 2.2×10^{-5} mg/kg bw/day under the UB scenario. For children, exposure estimates ranged from 1.3×10^{-6} to 1.8×10^{-5} mg/kg bw/day under the LB scenario and from 1.3×10^{-5} to 2.7×10^{-5} mg/kg bw/day under the UB scenario. Cumulative exposure was estimated at 3.0×10^{-5} and 7.4×10^{-5} mg/kg bw/day for adults and 3.6×10^{-5} and 9.0×10^{-5} mg/kg bw/day for children under the LB and UB scenarios, respectively.

For adults, *HQc* values for individual pesticides ranged from 5.4×10^{-7} to 0.0004 under the LB scenario and from 1.4×10^{-6} to 0.0011 under the UB scenario. For children, *HQc* values ranged from 6.6×10^{-7} to 0.0005 and from 1.7×10^{-6} to 0.0014 under the LB and UB scenarios, respectively. Pesticide-specific *HQc* values under the UB scenario are presented in Table S5. All individual *HQc* values remained well below 1 across both exposure scenarios and consumer groups. Under the UB scenario, *Hlc* values were 0.0028 for adults and 0.0035 for children. Fluopyram and pyrimethanil were the major contributors to *Hlc*, accounting for 39% and 33%, respectively, in both consumer groups. The relative contributions of individual pesticides to the deterministic *Hlc* and *Hla* are shown in Fig. 5. Thus, neither individual nor cumulative chronic exposure through onion consumption indicated a health concern under the deterministic assessment.

The low chronic risk estimates observed in the present study are consistent with previous assessments of pesticide exposure through onion consumption. Lučić and Onjia (2025) reported *Hlc* values ranging from 5.19×10^{-5} to 2.40×10^{-2} for adults and from 9.68×10^{-5} to 4.48×10^{-2} for children following the combined assessment of onions and leeks in Serbia, with mean values of 3.31×10^{-3} and 6.18×10^{-3} , respectively. The UB *Hlc* values obtained in the present study (0.0028 for adults and 0.0035 for children) were of a similar order of magnitude to the mean estimates reported in that study. A study based on 5731 onion samples collected in Egypt between 2021 and 2024 also reported low chronic dietary exposure, with the highest estimate corresponding to only 2.27% of the ADI (Malhat et al., 2025). Chronic dietary exposure estimates based on EU pesticide monitoring data also remained below the respective health-based guidance values (EFSA, 2024). Despite differences in residue profiles, consumption data, and exposure-assessment approaches, all reported estimates remained below the relevant health-based guidance values.

Probabilistic assessment further supported the findings of the deterministic analysis. The simulated *Hlc* distributions remained well below 1 for both consumer groups (Fig. 6). For adults, *Hlc* values at P5, P50, and P95 were 1.63×10^{-6} , 5.35×10^{-5} , and 0.00289, respectively, compared with 1.76×10^{-6} , 5.68×10^{-5} , and 0.0035 for children. Although *Hlc* estimates were consistently higher for children, including at the upper end of the modelled distributions, P95 values remained well below 1 for both consumer groups, indicating no appreciable chronic health concern.

The relative contributions of individual pesticides to the probabilistic *Hlc* were similar for adults and children (Fig. 7). Fluopyram was the principal contributor, followed by pyrimethanil, with the two pesticides together accounting for 80.4% and 80.6% of *Hlc* in adults and children, respectively. Boscalid (12.7–13.6%) and fluopicolide (5.5–6.6%) contributed to a lesser extent. This pattern was consistent with the deterministic assessment, in which fluopyram and pyrimethanil together accounted for 72% of *Hlc* in both consumer groups.

Their dominant contributions, despite boscalid being the most frequently detected residue, indicate that occurrence frequency alone does not determine the contribution of an individual pesticide to cumulative chronic risk. Residue concentrations and pesticide-specific health-based guidance values also influence the resulting risk estimates.

The low chronic risk indicated by the probabilistic assessment is consistent with previous findings for pesticide exposure through onion consumption. Mahmudiono et al. (2024) reported median total target hazard quotient values of 0.004 for adults and 0.02 for children in onion samples from Iran, with both estimates remaining below 1. Lučić and Onjia (2025) similarly reported Monte Carlo-derived *Hlc* values below 1 for all consumer groups assessed, although higher estimates were observed for children than for adults. In another study from Iran, *Hlc* values of 0.0210 and 0.0999 were estimated for adults and children, respectively, with all pesticide-specific *HQc* values also remaining below 1 (Gordan et al., 2025). Although direct comparison is constrained by differences in residue occurrence, consumption inputs, population characteristics, and probabilistic modelling approaches, the risk estimates reported across these studies remained below the threshold of concern.

Acute dietary risk estimates were also below the relevant reference thresholds for all detected pesticides. *HQa* values ranged from 0.0001 to 0.0408 for adults and from 0.0002 to 0.0910 for children (Table S5). Boscalid yielded the highest *HQa* in both consumer groups and was also the predominant contributor to the *Hla* (Fig. 5). Even the highest estimate remained well below 1, indicating no appreciable acute health concern under the conservative assessment approach applied for pesticides for which an ARfD has not been established. The low acute risk estimates obtained in the present study are consistent with previous findings for pesticide residues in onion. Lučić and Onjia (2025) reported *HQa* values ranging from 1.8×10^{-4} to 0.121 for adults and from 3.26×10^{-4} to 0.216 for children in a combined assessment of onions and leeks, with all estimates remaining below 1. Acute exposure assessments based on EU pesticide monitoring data also showed no exceedance of the available acute health-based reference values for onion (EFSA, 2024).

Conclusion

Pesticide residues were detected in approximately one-third of the onion samples analysed, with multiple residues occurring in most positive samples. None of the detected residues exceeded the EU MRLs. In addition, all five detected pesticides were classified within the low-risk category based on the risk-ranking assessment. Deterministic assessment indicated low chronic and acute dietary risks for both adults and children, while probabilistic modelling confirmed that cumulative chronic risk remained well below the threshold of concern, including at the upper end of the modelled exposure distributions. The predominance of fluopyram and pyrimethanil in cumulative chronic risk, despite boscalid being the most frequently detected pesticide, showed that detection frequency alone does not reflect the contribution of individual pesticides to dietary risk. These findings highlight the importance of considering residue occurrence, regulatory compliance, and dietary exposure together when interpreting pesticide monitoring data. Continued surveillance across geographical regions and sampling periods remains important for identifying changes in residue patterns and supporting risk-based monitoring of onion safety throughout the postharvest supply chain.

Declarations

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declarations

Conflicts of interest

The authors declare no competing interests.

Funding information

Author contributions

Tuba Buyuksirit-Bedir: Investigation, Formal analysis, Data curation, Writing–original draft. Eylem Odabas: Investigation, Validation, Visualization, Software, Data curation, Writing–original draft. Ozgur Golge: Investigation, Formal analysis, Validation, Software. Bulent Kabak: Conceptualization, Methodology, Investigation, Writing–review and editing.

Data availability

The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Information files.

Table 1

Tables 1 is available in the Supplementary Files section.

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Figures



Figure 1

QuEChERS-based sample preparation and analytical procedure for pesticide determination in onion samples.

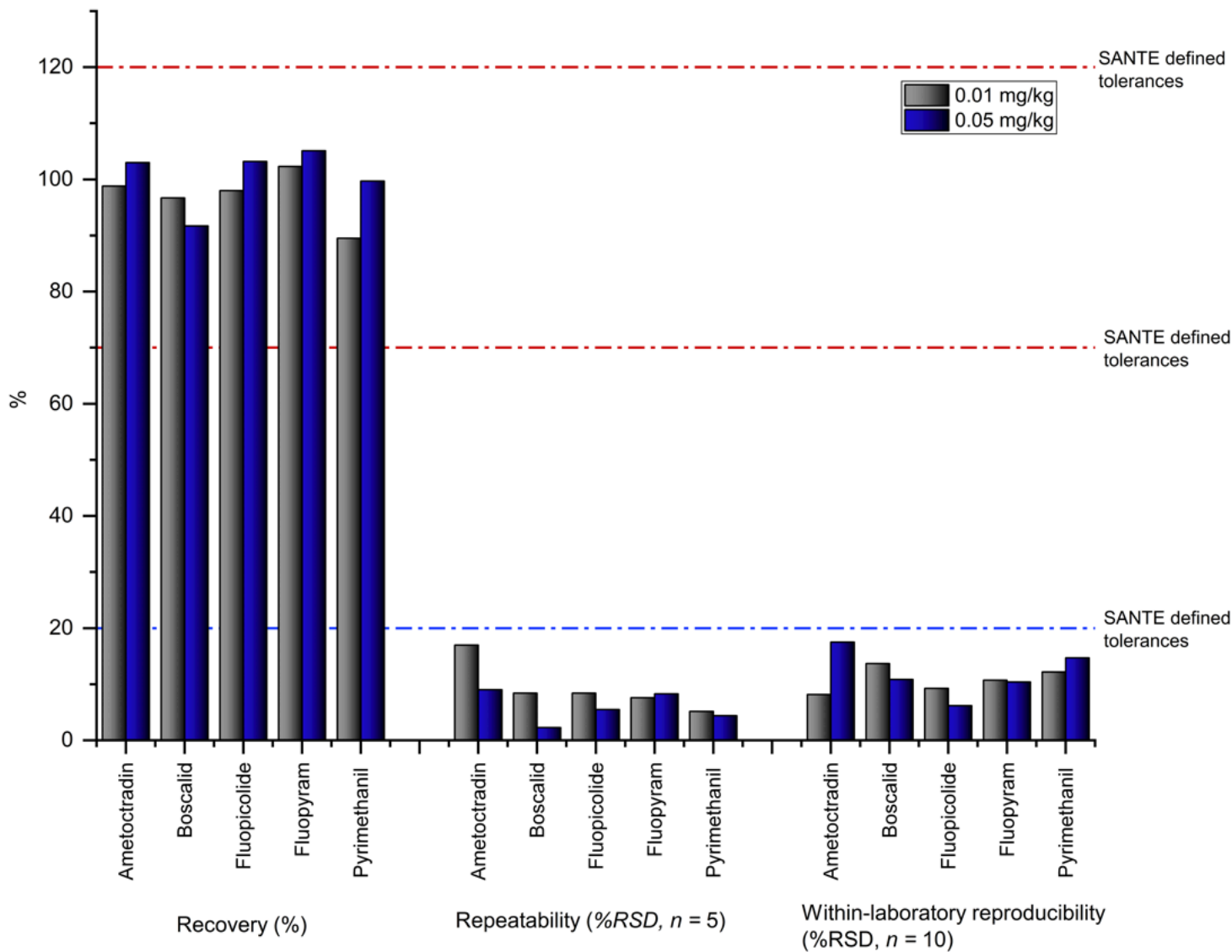


Figure 2

Recovery, repeatability, and within-laboratory reproducibility of the analytical method for the detected pesticides at two fortification levels, with the corresponding SANTE acceptance criteria.

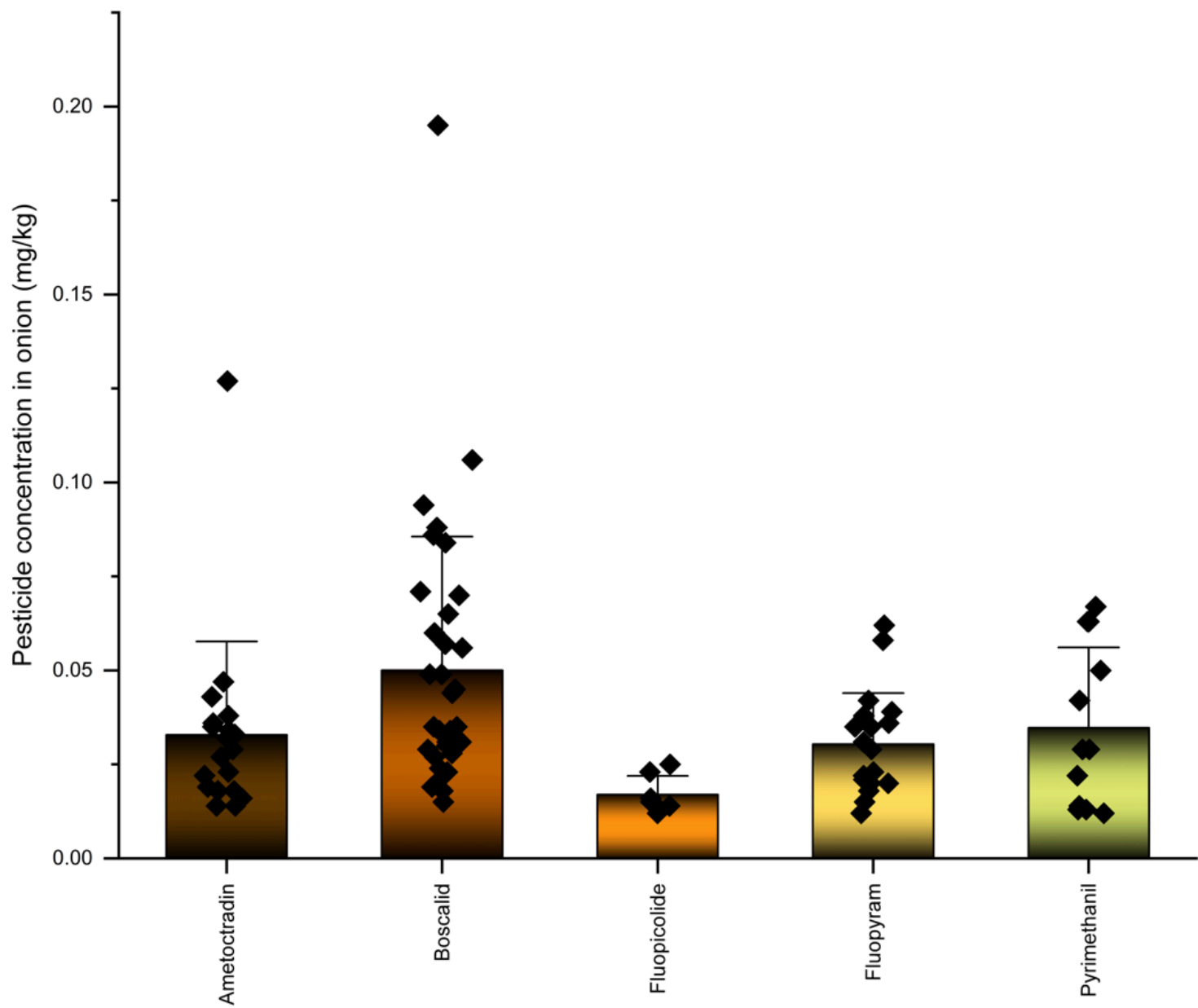


Figure 3

Distribution of pesticide residue concentrations in positive onion samples.

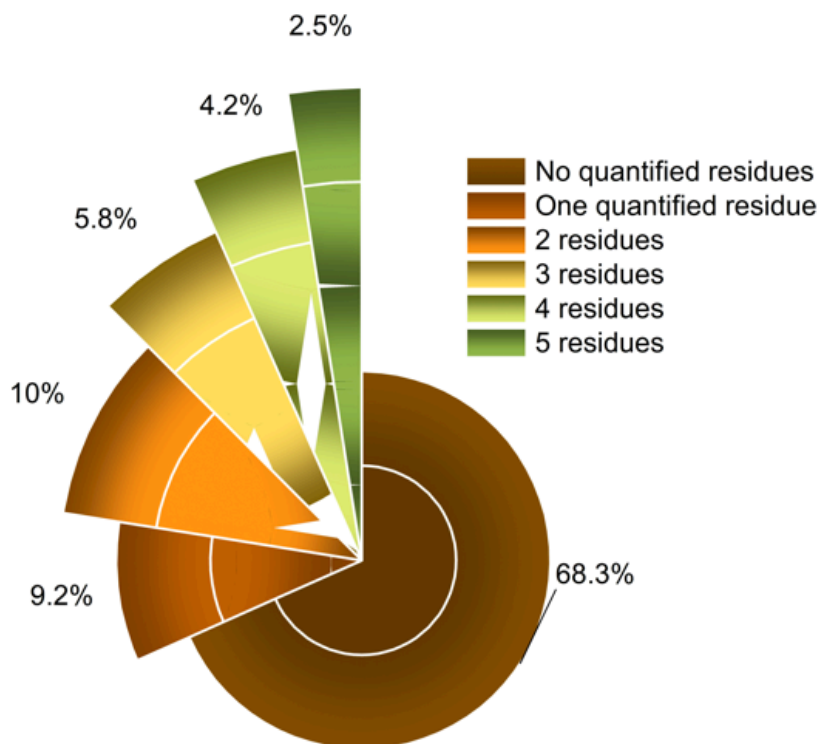


Figure 4

Distribution of onion samples according to the number of quantified pesticide residues.

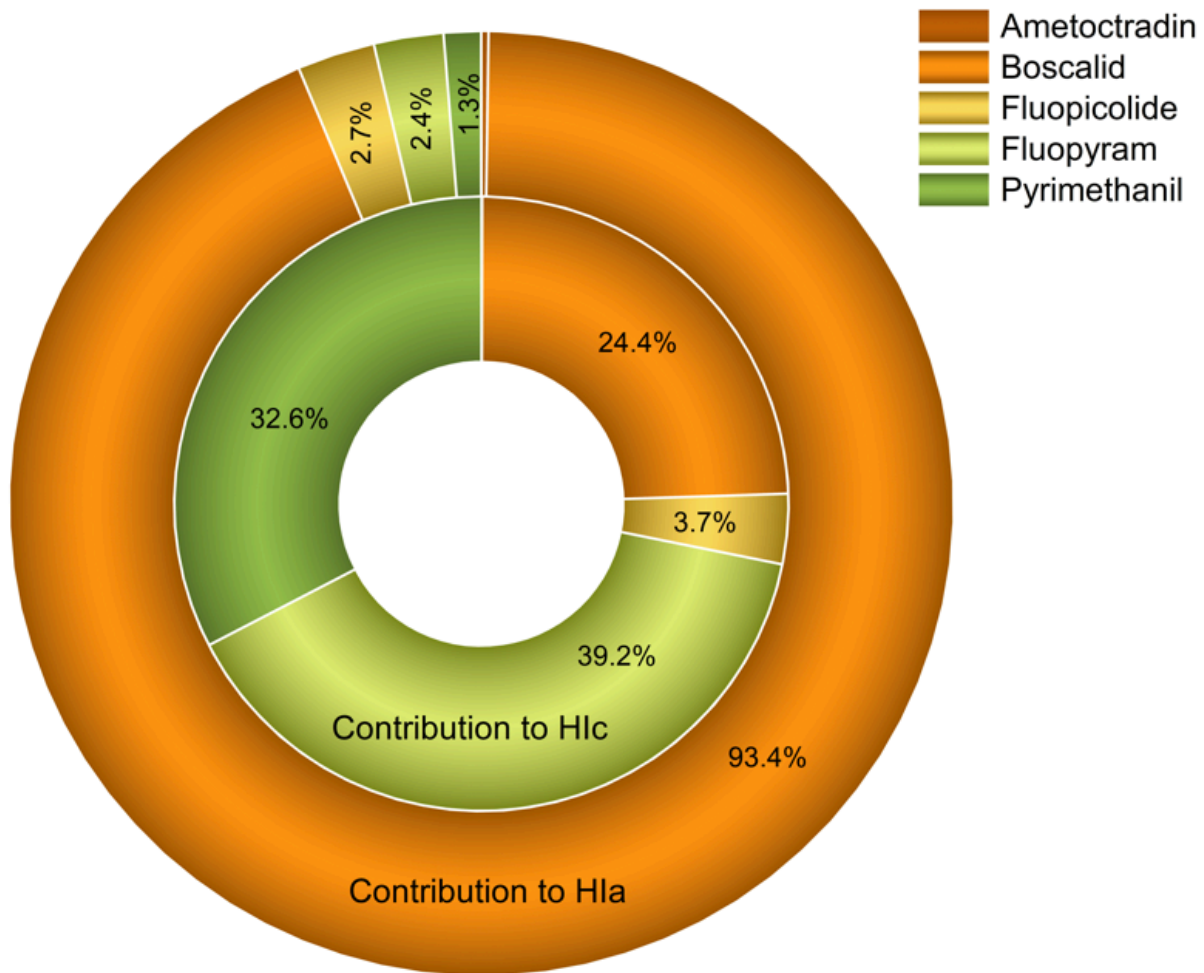


Figure 5

Relative contributions of individual pesticides to the acute (*Hla*) and chronic (*Hlc*) hazard indices for onion consumption.

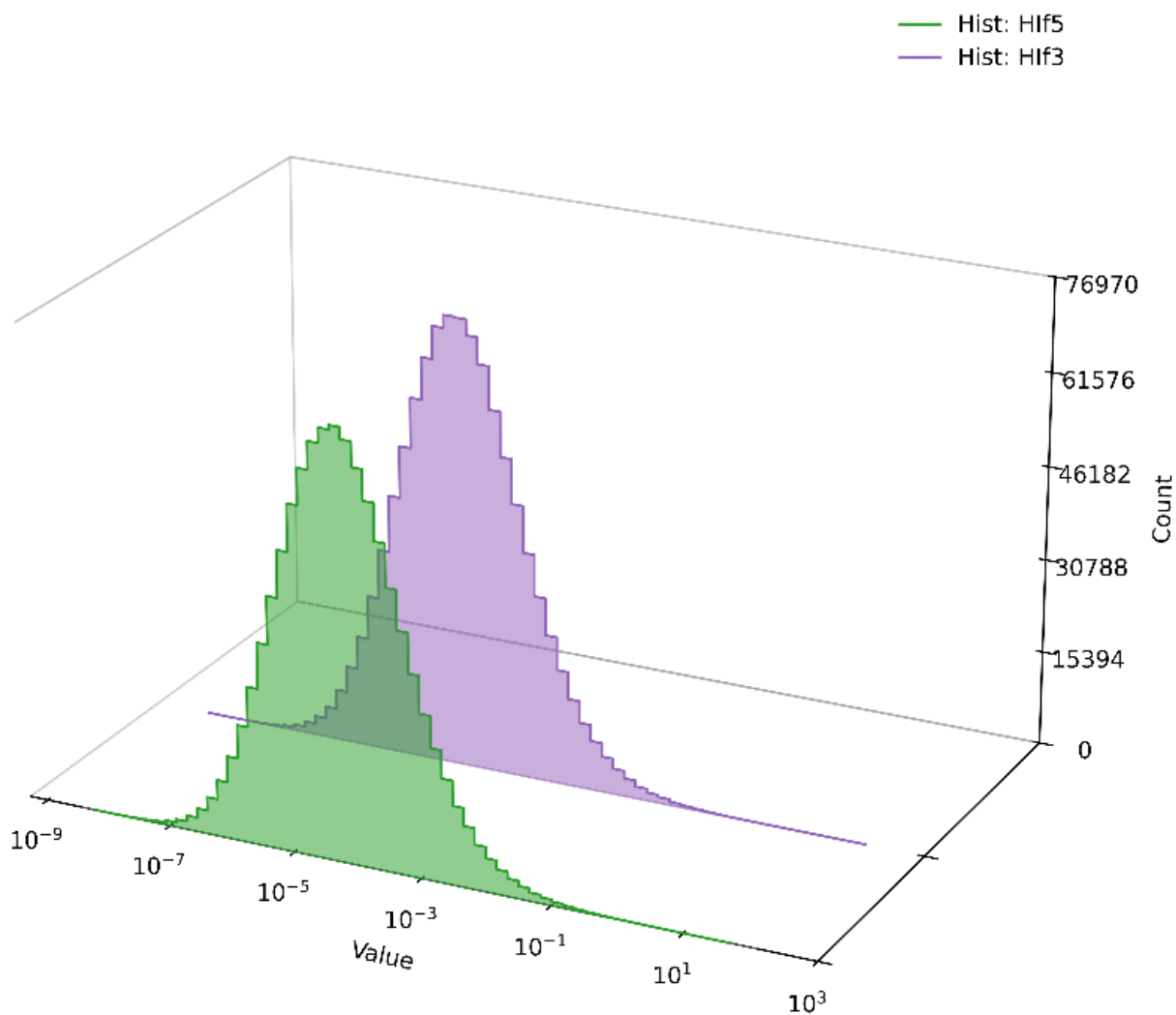


Figure 6

Probability distributions of the cumulative chronic hazard index (Hlc) for adult and child consumers obtained by Monte Carlo simulation. The distributions labelled Hlf5 and Hlf3 correspond to adult and child consumers, respectively.

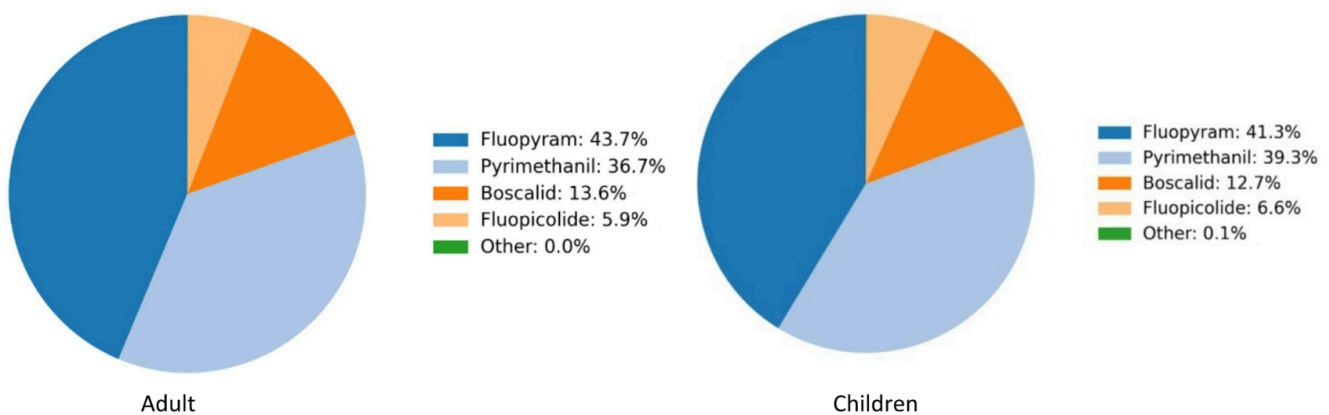


Figure 7

Relative contributions of individual pesticides to the cumulative chronic hazard index (*Hlc*) for adult and child consumers under the probabilistic exposure assessment. Percentages indicate the relative contribution of each pesticide to *Hlc*.

Supplementary Files

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