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Pesticide residues in tea and consumer exposure: health risk assessment*

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Abstract

Tea is one of the most widely consumed beverages worldwide, including in Poland. Despite well-documented health benefits, tea consumption may contribute to dietary exposure to chemical contaminants, for example pesticide residues. This study aimed to assess consumer health risk associated with tea contaminated with pesticide residues, based on official monitoring data. The analysis used data from the national official monitoring and control programme for pesticide residues in tea (Poland, 2022, NIPH-NIH/NIZP-PZH report). Chronic exposure assessment was performed using mean and 95th percentile residue concentrations of selected pesticides (e.g., bifenthrin, chlorfenapyr, thiamethoxam, folpet). Estimated daily intake (EDI) was calculated, and non-carcinogenic risk was characterised using THQ and HI relative to toxicological reference values (ADI). Acute risk results (ARfD) for individual samples exceeding MRLs were also discussed. For compounds with available ADI values, chronic exposure was low and indicated no non-carcinogenic risk (THQ < 1, HI < 1) for both mean and conservative (P95) scenarios. For isolated MRL exceedances, acute exposure did not exceed ARfD in critical populations. Anthraquinone required a precautionary interpretation due to the lack of established toxicological reference values, limiting quantitative risk characterisation. Based on official 2022 data, no health concern was identified for chronic or acute exposure to the assessed pesticide residues via tea consumption. Continued monitoring, improved mixture-risk approaches, and attention to substances with toxicological data gaps are recommended.

Keywords: tea, pesticide residues, dietary exposure, risk assessment

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INTRODUCTION

Tea is one of the most widely consumed beverages worldwide. Over the past decade, the global area of tea plantations has exceeded 5 million hectares, and annual production has surpassed 6 million tons (Czarniecka-Skubina et al. 2022, Kosoń et al. 2024, Chen, Luo 2025). More than 700 chemical compounds and 27 mineral elements have been identified in tea. Minimally processed teas (white, green, and red) are particularly valued due to their high content of polyphenols, catechins, theaflavins, and essential minerals such as potassium, magnesium, calcium, and manganese (Pan et al. 2022, Czarniecka-Skubina et al. 2022, Zohora, Arefin 2022).

Numerous experimental and epidemiological studies have demonstrated potential health-promoting effects of tea consumption, including a reduced risk of certain cancers, cardiovascular diseases, atherosclerosis, coronary heart disease, dyslipidemia, hypertension, and neurodegenerative disorders (Peters et al. 2001, Vuong 2014, Hajiaghaalipour et al. 2015, Pan et al. 2017, Pastoriza et al. 2017, Rangi et al. 2019, Umeda et al. 2021, Zhang et al. 2021, Chen 2022). These beneficial effects are mainly attributed to tea polyphenols, particularly catechins and theaflavins, which exhibit strong antioxidant properties and chemopreventive potential.

However, like other plant-derived products, tea may also constitute a source of exposure to chemical contaminants, including pesticide residues and other xenobiotics (Chmielewski et al. 2021, Brodziak-Dopierała, Fischer 2022, Grządka et al. 2024, Kaczyński et al. 2024, Chmielewski et al. 2025, 2025a, Żeber-Dzikowska et al. 2025). Contamination of tea plants may result from the intensification of agricultural production, the application of plant protection products, environmental pollution, as well as processing, storage, and transportation conditions (Ochwanowska et al. 2019, Gworek et al. 2024, Bąk-Badowska et al. 2025, Żeber-Dzikowska et al. 2025). The large leaf surface area of tea plants facilitates the adsorption and accumulation of environmental contaminants, including pesticide residues, dioxins, and furans (Huang et al. 2019, Zhang et al. 2021a).

In recent years, the presence of pesticide residues in agricultural products, including tea, has gained increasing attention in the context of public health and food safety (Philippe et al. 2021, Yao et al. 2022, Chmielewski et al. 2025, 2025a, Żeber-Dzikowska et al. 2025). Within the European Union, harmonized legislation establishes maximum residue levels (MRLs), and Member States implement coordinated monitoring programs. In Poland, the Chief Sanitary Inspectorate is responsible for food safety within the Rapid Alert System for Food and Feed (RASFF), reporting identified irregularities to the European Commission (Chmielewski et al. 2025, 2025a, Żeber-Dzikowska et al. 2025). In 2025, public warnings were issued concerning the presence of anthraquinone in certain batches of black tea (GIS 2025), highlighting the importance of continuous surveillance of this product category.

Poland ranks among the European countries with relatively high tea consumption (Brodziak-Dopierała, Fischer 2022, Kosoń et al. 2024). It is estimated that an average Polish citizen consumes approximately 94 liters of tea per year (Grządka et al. 2024). Data from the Central Statistical Office (GUS 2024) indicate that average monthly tea consumption in households between 2020 and 2024 ranged from approximately 0.04 to 0.05 kg per person, with higher consumption observed in certain socio-economic groups.

Given the high frequency of tea consumption, even low levels of contamination may be relevant in the context of long-term dietary exposure. Contemporary food safety management is based on a risk analysis framework, including hazard identification, exposure assessment, and risk characterization (Philippe et al. 2021, Yao et al. 2022, Fan et al. 2023). This approach integrates toxicological reference values (ADI, ARfD) with actual consumption data and measured residue levels in food products.

Considering the widespread consumption of tea and the potential exposure to mixtures of pesticide residues, systematic monitoring and quantitative health risk assessment across different population groups are warranted.

The present study aimed to assess the health risk associated with the consumption of tea available on the Polish market contaminated with pesticide residues, based on data derived from official control and national monitoring programs.

MATERIALS AND METHODS

Samples for compliance testing with maximum residue levels (MRLs) within the coordinated national monitoring programme and official food control in Poland were collected by inspectors of the State Sanitary Inspection (SSI) pursuant to Article 27 of Regulation (EC) No 396/2006, in accordance with the Regulation of the Minister of Health of 17 October 2007 on sampling of food for the determination of pesticide residue levels, implementing Commission Directive 2002/63/EC of 11 July 2002. Sampling was conducted in line with Commission Implementing Regulation (EU) No 2021/601 of 13 April 2021.

In 2022, a total of 160 tea samples were analyzed for the presence of 320 pesticides, including 72 samples collected from the domestic market and 88 samples collected within border control procedures. Among these, 145 samples originated from third countries, while the country of origin of 15 samples was not established.

Analytical determinations were performed in SSI laboratories using the following techniques:

- GC-ECD (gas chromatography with electron capture detection),

- GC-MS/MS (gas chromatography coupled with tandem mass spectrometry),
- HPLC-FL (high-performance liquid chromatography with fluorescence detection) for carbendazim and thiabendazole,
- HPLC-MS/MS (high-performance liquid chromatography coupled with tandem mass spectrometry),
- UV/VIS spectrophotometry for the determination of dithiocarbamate residues (Struciński et al. 2022).

The analytical material consisted of data derived from the National Monitoring Programme and Official Food Control for pesticide residues in 2022, as reported by the National Institute of Public Health – National Institute of Hygiene – National Research Institute (NIZP-PZH) (Struciński et al. 2022).

Data on average food consumption in Poland included in the PRIMo rev. 3.1 model refer only to the general population (aged 1-96 years, mean body weight 62.80 kg), use of EFSA 2018 and is based on dietary surveys conducted more than 20 years ago (Szponar et al. 2008). Therefore, for the chronic exposure assessment, several additional dietary scenarios potentially comparable to the national diet were included in order to increase the number of exposure scenarios (Struciński et al. 2022).

In addition to the Polish diet, the following dietary models were considered for chronic exposure estimation:

- German diet (BfR 2011):
 - children aged 2-4 years (mean body weight 16.15 kg),
 - general population aged 14-80 years (mean body weight 76.37 kg),
 - women aged 14-50 years (mean body weight 67.47 kg).

United Kingdom diet (HSE 2006):

- infants aged 6-12 months (mean body weight 8.70 kg),
- toddlers aged 18 months – 4 years (mean body weight 14.60 kg),
- adults aged 19-64 years (mean body weight 76.00 kg),
- adult vegetarians (mean body weight 66.70 kg).

GEMS/Food FAO/WHO Cluster Diet G08 (FAO/WHO 2012), covering Austria, Spain, Germany, and Poland (mean body weight 60.00 kg).

The most critical diet, defined as the one with the highest mean consumption of the product in the EU expressed in g kg⁻¹ body weight per day, if different from those listed above.

In the tables, estimated daily intakes of pesticide residues expressed as %ADI equal to 0.00% should be interpreted as <0.01%.

The health risk assessment related to exposure to pesticide residues in tea was conducted for selected consumer groups using acceptable daily intake values expressed per kilogram of body weight. Exposure was assessed assuming the consumption of tea with known concentrations of identified pesticide residues. The average daily tea consumption was based on available statistical data from the Central Statistical Office (Table 1). Data included in the risk assessment (mean concentration and 95th percentile

of pesticide residues, estimated daily intake, and average daily consumption) are presented in Tables 1, 2 and 3 (Struciński et al. 2022).

Table 1
Mean concentrations and 95th percentile values of pesticide residues detected in tea (NIZP-PZH Report)

Pesticide	Mean concentration (mg kg ⁻¹)	95 th percentile (P95) (mg kg ⁻¹)	Maximum residue level (MRL) in force in 2022 (mg kg ⁻¹)
Tea			
Bifenthrin	0.109	0.480	30
Chlorfenapyr	0.108	0.530	50
Thiamethoxam	0.045	0.161	20
Folpet	0.062	0.180	0.1
Anthraquinone	0.008	0.019	0.02

Source: Struciński et al. 2022

Table 2
Estimated daily intake (EDI) expressed as %ADI for tea (based on the NIZP-PZH Report)

Pesticide	Tea									
	DE child	UK infant	UK toddler	PL general population	UK adult	UK adult vegetarian	GEMS/ Food G08	DE general population	DE women aged 14-50 years	FR adult [#]
Bifenthrin ADI 0.015 mg kg ⁻¹ bw day ⁻¹ EFSA 2011, 2015										
Mean (%)	0.01	0.04	0.02	-	0.04	0.04	0.02	0.00	0.02	0.10
P95 (%)	0.03	0.18	0.09	-	0.17	0.16	0.09	0.10	0.10	0.45
Chlorfenapyr ADI 0.015 mg kg ⁻¹ bw day ⁻¹ ECCO 1999										
Mean (%)	0.01	0.04	0.02	-	0.04	0.04	0.02	0.02	0.02	0.10
P95 (%)	0.04	0.20	0.10	-	0.19	0.17	0.10	0.11	0.11	0.50
Thiamethoxam ADI 0.026 mg kg ⁻¹ bw day ⁻¹ EC 2003; EFSA 2017										
Mean (%)	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.01
P95 (%)	0.00	0.01	0.00	-	0.01	0.01	0.01	0.01	0.01	0.03
Folpet ADI 0.1 mg kg ⁻¹ bw day ⁻¹ EFSA 2009; 2014										
Mean (%)	0.00	0.01	0.00	-	0.01	0.01	0.01	0.01	0.01	0.02
P95 (%)	0.01	0.04	0.02	-	0.03	0.03	0.02	0.02	0.02	0.09

Source: Struciński et al. (2022)

[#] Results for the critical diet

Average daily tea consumption based on the NIZP-PZH Report

Tea			
Diet	mean body weight (kg)	daily consumption (g kg ⁻¹ bw day ⁻¹)	daily consumption (g person ⁻¹ day ⁻¹)
Child			
DE child	16.15	0.0100	0.1615
UK infant	8.70	0.0575	0.5000
UK toddler	14.60	0.0274	0.4000
Adult			
PL general population	62.80	data not available	data not available
UK adult	76.00	0.0539	4.1000
UK adult vegetarian	66.70	0.0495	3.3000
GEMS/Food G08	60.00	0.0288	1.7300
DE general population	76.37	0.0304	2.3204
DE women aged 14-50 years	67.47	0.0298	2.0114
FR adult [#]	66.40	0.1405	9.3292

* Source: FAO/WHO GEMS/Food Cluster Diet G06 (2012), Struciński et al. (2022)

¹ Results for the critical diet

RESULTS AND DISCUSSION

Health risks associated with the consumption of the identified pesticide residues in tea were evaluated based on the following indicators:

- Estimated daily intake (EDI),
- Target hazard quotient (THQ),
- Hazard index (HI).

The daily intake of a given contaminant (EDI) depends both on its concentration in tea and on the daily consumption of the product. The EDI (expressed in micrograms per kilogram body weight per day) was calculated using the following equation:

$$EDI = C \times C_{on} / BW \quad (1)$$

where: C (µg kg⁻¹) – the average concentration of a given contaminant in the collected tea samples,

C_{on} (kg person⁻¹ d⁻¹) – the daily average consumption of tea,

BW (kg person⁻¹) – represents body weight; in the present calculations, a mean adult body weight of 62.8 kg was assumed.

The non-carcinogenic risk for adult consumers resulting from tea consumption was estimated using the following equation:

$$THQ_p = EDI/ADI \quad (2)$$

where: THQ_p – represents the target hazard quotient for pesticides,
 THQ_{hm} – refers to the target hazard quotient for heavy metals,
 ADI (acceptable daily intake) – values were obtained from the NIZP-PZH Report (Struciński et al. 2022).

The potential health risk resulting from exposure to a mixture of chemical substances was assessed using the hazard index (HI), which is widely applied in cumulative risk assessment. The HI for mean daily intake was calculated as follows:

$$HI = \sum_{i=1}^n THI_i \quad (3)$$

THQ is recognized as one of the principal parameters for evaluating a non-carcinogenic risk associated with the consumption of contaminated food (Liang et al. 2019). The calculated THQ values for the analyzed pesticides are presented in Table 4.

Table 4

Estimated daily intake (EDI), target hazard quotient (THQ), and maximum residue levels (MRLs) for selected pesticide active substances in tea consumed by adults (A) and children (Ch)

Product	EDI		THQ		NDP
	Active substance (pesticide type)				
	A	Ch	A	Ch	
Tea	Bifenthrin				
	1.53 x 10 ⁻⁵	6.26 x 10 ⁻⁶	1.02 x 10 ⁻³	4.18 x 10 ⁻⁴	30
	Chlorfenapyr				
	1.52 x 10 ⁻⁵	6.21 x 10 ⁻⁶	1.01 x 10 ⁻³	4.14 x 10 ⁻⁴	50
	Thiamethoxam				
	6.32 x 10 ⁻⁶	2.59 x 10 ⁻⁶	2.43 x 10 ⁻⁴	9.96 x 10 ⁻⁵	20
	Folpet				
	8.71 x 10 ⁻⁶	3.56 x 10 ⁻⁶	8.71 x 10 ⁻⁵	3.56 x 10 ⁻⁵	0.1
Anthraquinone					
1.12 x 10 ⁻⁶	4.60 x 10 ⁻⁷	-	-	0.02	

Table 4 presents the estimated daily intake (EDI) and target hazard quotient (THQ) values for selected pesticide residues detected in tea, calculated on the basis of their mean concentrations in monitoring samples. The assessment was performed for adult (A) and child (Ch) populations.

All THQ values calculated based on the mean pesticide concentrations were significantly below 1 (range 3.56 × 10⁻³–1.02 × 10⁻³), indicating the absence of a chronic non-carcinogenic risk for both adult and child popula-

tions. It is generally accepted that when the THQ value is less than 1, it is unlikely that individuals are exposed to a toxic level of a given contaminant in food products, and therefore, adverse health effects are not expected (Li-ang et al. 2019).

Based on the calculated indicators, all THQ values were below 1, indicating the absence of a non-carcinogenic health risk associated with the consumption of tea containing the analyzed pesticide residues, assuming exposure to a single active substance. However, dietary exposure rarely occurs in isolation. Therefore, in addition to the evaluation of individual substances, a cumulative assessment was performed to account for potential combined effects of co-occurring pesticide residues in tea. The cumulative HI, calculated as the sum of individual THQ values under the assumption of dose additivity, remained substantially below the level of concern (HI = 1), indicating that combined exposure does not pose a non-carcinogenic risk to consumers.

The calculated HI values further confirm that adverse health effects are not expected as a result of tea consumption containing the analyzed pesticide residues. Based on the presented analysis and the results reported by NIZP-PZH (Struciński et al. 2022), it can be concluded that chronic dietary exposure to pesticide residues in tea does not constitute a health risk for consumers under the assessed consumption scenarios.

Chronic dietary exposure (EDI)

For adults, EDI values ranged from: 1.12×10^{-6} to 1.53×10^{-5} mg kg⁻¹ bw day⁻¹, whereas for children they ranged from: 4.60×10^{-7} to 6.26×10^{-6} mg kg⁻¹ bw day⁻¹.

The highest EDI values were observed for bifenthrin and chlorfenapyr, reflecting their relatively higher mean concentrations in tea (0.109 mg kg⁻¹ and 0.108 mg kg⁻¹, respectively). In contrast, the lowest EDI values were associated with anthraquinone, which exhibited the lowest mean concentration among the analyzed substances.

Although the absolute consumption of tea is generally lower in children than in adults, exposure expressed on a body weight basis (mg kg⁻¹ bw day⁻¹) results in proportionally higher intake levels in the pediatric population. This outcome reflects the standard body weight normalization principle applied in dietary risk assessment. Due to their lower body mass and ongoing physiological development, children are routinely considered a potentially more susceptible subgroup in exposure assessments. Consequently, inclusion of pediatric scenarios represents a conservative and scientifically justified approach in the characterization of dietary risk.

Toxicological interpretation in the context of the established risk assessment framework

Chronic dietary exposure and risk characterization

The chronic dietary exposure assessment demonstrated that the calculated estimated daily intake (EDI) values for the analyzed pesticide residues were several orders of magnitude below the corresponding acceptable daily intake (ADI) values established by regulatory authorities (EFSA 2009, 2011, 2014, 2015, 2017, EC 2003, ECCO 1999, Struciński et al. 2022).

All target hazard quotient (THQ) values remained substantially below the threshold value of 1, which is conventionally interpreted as the level indicating potential non-carcinogenic concern. The THQ values obtained ($10^{-5} - 10^{-3}$) confirm that chronic exposure through tea consumption constitutes only a small fraction of the toxicological reference values.

Given that ADI values are derived from experimentally established NOAELs with the application of standard uncertainty factors (typically 100-fold), exposure levels below ADI inherently incorporate a significant margin of safety. From a regulatory toxicology perspective, such exposure levels are considered to present no appreciable health risk under a threshold-based model of toxicity.

Mechanisms of action and their significance in toxicological risk assessment

The evaluated substances act through mechanisms consistent with threshold toxicology:

- Bifenthrin – modulation of voltage-gated sodium channels, with neurotoxic effects occurring at substantially higher doses (EFSA 2011, 2015);
- Chlorfenapyr – disruption of mitochondrial oxidative phosphorylation following metabolic activation (ECCO 1999);
- Thiamethoxam – nicotinic acetylcholine receptor agonism in insects, with lower receptor affinity in mammals (EC 2003; EFSA 2017);
- Folpet – multi-site reactivity, including interaction with sulfhydryl groups, with toxicological endpoints primarily observed at higher exposure levels (EFSA 2009, 2014).

The exposure levels estimated in this study remain several orders of magnitude below doses associated with systemic or target-organ toxicity in toxicological evaluations. Therefore, under current exposure scenarios, the likelihood of biologically relevant adverse effects is negligible.

Cumulative risk assessment

The cumulative hazard index (HI), calculated as the sum of individual THQ values (Struciński et al. 2022), amounted to:

$$\begin{aligned} \text{HI}_a &= 2.36 \times 10^{-3}, \\ \text{HI}_h &= 9.67 \times 10^{-4}. \end{aligned}$$

These values remain approximately three orders of magnitude below the level of concern ($\text{HI} = 1$). According to the dose-additivity principle commonly applied in cumulative risk assessment, an HI below unity indicates that combined exposure does not exceed toxicological reference thresholds.

Although mixture effects may theoretically involve additive, synergistic, or antagonistic interactions, regulatory practice primarily applies conservative dose-additive assumptions. Given the very low magnitude of the calculated HI values, even potential interaction effects are unlikely to reach biologically relevant levels.

Uncertainty analysis and precautionary considerations

In accordance with regulatory risk assessment principles, several sources of uncertainty must be acknowledged:

- variability in tea consumption patterns among different population groups,
- differences between pesticide concentrations in dry tea leaves and actual exposure from infusion,
- limited toxicological data for certain substances,
- potential interactions within pesticide mixtures.

A particular case concerns anthraquinone, for which no ADI has been established (Struciński et al. 2022, Valduga et al. 2024). The absence of a health-based guidance value precludes classical threshold-based risk characterization. While the calculated EDI values for anthraquinone were very low (approximately $10^{-6} \text{ mg kg}^{-1} \text{ bw day}^{-1}$), uncertainties regarding its toxicological profile and possible genotoxic or carcinogenic properties justify a precautionary approach and continued monitoring.

Nevertheless, considering the magnitude of the estimated exposure, the quantitative contribution of anthraquinone to overall dietary risk appears minimal.

Final risk characterization in relation to toxicological reference values

Based on official monitoring data (Struciński et al. 2022) and toxicological reference values established by EFSA and related regulatory authorities (EFSA 2009, 2011, 2014, 2015, 2017, EC 2003, ECCO 1999), chronic dietary exposure to pesticide residues in tea available on the Polish market remains substantially below established health-based guidance values.

Under current consumption patterns and regulatory controls, no chronic non-carcinogenic health risk to consumers is indicated. Continued monitoring, particularly for substances lacking established toxicological reference

values, remains an essential component of a precautionary and science-based food safety system.

The results of the official control analyses (Struciński et al. 2022) identified four non-compliances with the established maximum residue levels (MRLs) in three tea samples (including one originating from China and two from India), as presented in Table 5.

Table 5

Results of the short-term (acute) risk assessment for MRL exceedances identified in tea

Compound	Concentration ± uncertainty	MRL (mg kg ⁻¹)	ARfD (mg kg ⁻¹ bw) (source)	Intake (% ARfD) (critical population ²)	
				child	adult
Acetamidrid	0.19 ± 0.1	0.05	0.025 (EFSA 2016)	0.8 (FR)*	0.4 (DE)*
				0.3 (NL)**	0.2 (NL)**
Tolfenpyrad	0.056 ± 0.028	0.01	0.01 (JMPR 2016)	0.6 (FR)*	0.3 (DE)*
				0.2 (NL)**	0.1 (NL)**
	0.079 ± 0.04			0.9 (FR)*	0.4 (DE)*
	0.091 ± 0.046			0.3 (NL)**	0.2 (NL)**
				1.0 (FR)*	0.5 (DE)*
	0.3 (NL)**	0.2 (NL)**			

* tea leaves[#], ** tea infusion

[#] In the PRIMo model, an incorrect large portion value for tea consumption in children was included (Ireland, 1.53 g kg⁻¹ bw). The correct value should be 1.1 g kg⁻¹ bw (France, children aged 11-14 years). Results for the critical diet are presented in bold (Struciński et al. 2022).

In the case of anthraquinone, a substance not included in Annex I to Council Directive 91/414/EEC pursuant to Commission Decision 2008/986/EC, long-term risk assessment was not performed. The presence of this compound in tea samples is unlikely to result from its intentional use in crop protection but rather from environmental contamination or improper drying processes (Struciński et al. 2022). Anthraquinone has an incompletely characterized toxicological profile, and its potential genotoxic or carcinogenic properties cannot be excluded (Valduga et al. 2024). Consequently, no toxicological reference values can be established, precluding classical threshold-based risk characterization. Therefore, any level of anthraquinone detected above the applicable MRL should be interpreted within a precautionary framework.

It was determined that potential acute (single-day) intake of acetamidrid and tolfenpyrad from a large portion of tea did not exceed the respective ARfD values in either children or adults. However, tolfenpyrad has not been notified or approved for use within the EU and has therefore not undergone evaluation at the Community level. Risk characterization based on ARfD

values established by JMPR FAO/WHO (2016) is thus associated with an additional degree of uncertainty (Struciński et al. 2022).

Based on the literature available at the time of the study, both short-term and long-term exposure to pesticide residues associated with tea consumption do not indicate a health risk for consumers under the assessed scenarios.

Adenuga et al. (2022) reported that concentrations of organochlorine pesticide (OCP) residues in medicinal teas exceeded MRLs in most samples, indicating a high potential for OCP accumulation. Their risk assessment showed the highest non-carcinogenic and carcinogenic risks for heptachlor epoxide and aldrin, respectively, with children being relatively more exposed than adults.

Szternfeld et al. (2023) observed that although more than 38% of dry tea leaf samples exceeded EU MRLs, risk assessment based on infusion levels did not indicate health concerns. Fan et al. (2023) reported hazard quotient values ranging from 0.47×10^{-3} to 1.1×10^{-3} %, also suggesting negligible chronic risk.

The study by Fan et al. (2023) showed that the most frequently detected pesticide residues were imidacloprid (35.2%), acetamiprid (26.7%), carbendazim (21.0%), bifenthrin (21.0%), and cyhalothrin (19.1%). Carbofuran was the only pesticide to exceed the maximum residue limit in a single sample. Based on the preliminary assessment of long-term exposure, the hazard ratio values of detected pesticides ranged from 0.47×10^{-3} to 1.1×10^{-3} %, indicating that these levels did not pose a risk to human health.

Kaczyński et al. (2024) detected 24 pesticides among 603 analyzed compounds, including nine withdrawn in Europe. Although 47% of tea samples contained residues and 2% exceeded EU MRLs, acute risk remained limited (maximum 17% of ARfD for linuron/mint/children).

The accumulation of pesticides in tea cultivation and their transfer into the food chain represent a global public health concern. Chronic dietary exposure to low levels of pesticide residues may contribute to cumulative body burden, particularly in regularly exposed populations.

Importantly, real-life exposure does not occur to single substances in isolation but rather to mixtures of residues with potentially overlapping or distinct mechanisms of action. Within the framework of cumulative risk assessment (CRA), regulatory practice generally applies the principle of dose addition, particularly for substances grouped within cumulative assessment groups (CAGs). This approach is conservative, assuming at least additive effects.

Nevertheless, toxicological interactions may theoretically include synergistic or antagonistic mechanisms, involving shared metabolic pathways (e.g., CYP450-mediated biotransformation), oxidative stress modulation, mitochondrial function, or receptor-mediated signaling (Alengebawy et al. 2021, Gou-

tam Mukherjee et al. 2022). Such mechanisms may modify internal exposure or biological response, particularly under conditions of chronic low-dose exposure.

Despite these theoretical considerations, the extremely low individual THQ values and the cumulative HI values obtained in the present study remain several orders of magnitude below the level of concern (HI = 1). This substantial margin of exposure considerably reduces the likelihood that mixture-related interactions could result in biologically relevant adverse effects under the assessed exposure conditions.

However, limited long-term experimental data on chronic low-dose mixture exposure remain a source of uncertainty in dietary risk assessment. Continued refinement of cumulative assessment methodologies and improved mechanistic understanding of mixture toxicity are therefore warranted to strengthen the scientific robustness of future evaluations.

CONCLUSIONS

The conducted assessment of chronic dietary exposure to selected pesticide residues in tea available on the Polish market indicates that the estimated intake levels remain substantially below established health-based guidance values (ADI). All calculated target hazard quotient (THQ) values were markedly lower than 1, and the cumulative Hazard Index (HI) remained well below the threshold of concern for both adults and children. These findings suggest that, under the adopted exposure assumptions, tea consumption does not pose a significant non-carcinogenic health risk to consumers.

The estimated exposure levels constituted only a small fraction of the corresponding ADI values, reflecting a considerable margin of safety relative to NOAEL-derived toxicological reference points. Even when applying a conservative additive approach to mixture exposure, the cumulative risk remained negligible.

However, some uncertainties should be acknowledged, including variability in consumption patterns, potential differences between residue concentrations in dry tea and brewed infusion, and limited toxicological data for some compounds (e.g., anthraquinone). Continuous monitoring of pesticide residues, especially in imported tea products, remains essential to ensure food safety.

Given the potential for cumulative exposure and mixture interactions, further research focused on long-term low-dose exposure and refinement of cumulative risk assessment methodologies is warranted. Maintaining systematic official control and monitoring programs is crucial for safeguarding public health and ensuring compliance with regulatory standards.

Author contributions

J.C. – designed research, J.C., B.G. – methodology, conceptualization, analyzed data and wrote the manuscript, B.G. – supervision, visualization, J.C, B.G. – review and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

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

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