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Health and environmental risk assessment of berry fruits contaminated with pesticide residues, including soil ecosystem exposure

Jarosław P. Chmielewski[1,2,A-D,F], Barbara Gworek[3,B-D,F], Halina Król[4,B,D,F], Roman Starz[5,B,D,F], Sławomir Józef Krzebietke[6,C,E-F], Magdalena Florek-Łuszczki[2,C,E-F]

[1] Department of Public Health, Academy of Medical Sciences of Applied and Holistic Sciences, Warsaw, Poland
[2] Department of Medical Anthropology, Institute of Rural Health, Lublin, Poland
[3] Department of Environmental Chemistry and Risk Assessment, Institute of Environmental Protection – National Research Institute, Warsaw, Poland
[4] Institute of Health Sciences, Collegium Medicum, Jan Kochanowski University, Kielce, Poland
[5] Faculty of Humanities, Jan Kochanowski University, Kielce, Poland
[6] Department of Agricultural and Environmental Chemistry, Faculty of Agriculture and Forestry, University of Warmia and Mazury, Olsztyn, Poland
A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article

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Abstract

Introduction and Objective. Pesticides, also known as plant protection products, are used to control pests, plant diseases, and weeds during crop cultivation and post-harvest handling. The aim of the study is evaluation of the health and environmental risks associated with pesticide residues in berry fruits (strawberries, raspberries, and blueberries) available in Poland in 2022.

Materials and Method. The study is based on the results of officially controlled, laboratory analyses of pesticide residues in berry fruits available on the Polish market in 2022, data on fruit consumption, and literature data concerning acceptable daily intake values (ADI). Estimated daily intake (EDI) and hazard quotients (HQ) were calculated to assess the chronic dietary risk. In addition, a screening-level environmental risk assessment was carried out for the same active substances, focusing on the soil compartment as the main sink of pesticide residues.

Results. The health risk assessment showed that all calculated EDI, HQ, and HI values for pesticide residues in strawberries, raspberries, and blueberries consumed in Poland in 2022 were several orders of magnitude below the threshold of concern (HQ < 1). The environmental risk assessment indicated that most fungicides (boscalid, cyprodinil, fludioxonil, fluopyram) posed low risk to soil organisms (RQ < 1), even under conservative scenarios. However, acetamiprid exceeded the risk threshold at higher assumed soil concentrations (MEC = 0.10 mg/kg), suggesting potential ecological concern for sensitive soil invertebrates, such as collembolans.

Conclusions. The study showed that pesticide residues in strawberries, raspberries, and blueberries available in Poland in 2022 did not pose a chronic health risk to consumers. Environmental risk assessment indicated low risk for most fungicides; however, acetamiprid exceeded the safety threshold under higher soil contamination scenarios, suggesting potential concern for soil invertebrates.

Key words
health and environmental risk, berry fruits, pesticide residues

INTRODUCTION

Pesticides, also referred to as plant protection products, are substances intended to destroy, repel, prevent or mitigate the effects of harmful agents during plant cultivation, before or after harvest, and to maintain product quality during storage and transport. They include antimicrobial agents, defoliants, disinfectants, fungicides, herbicides, insecticides, growth regulators, and molluscicides, among others [1]. During agricultural treatments, pesticides are applied directly onto plants or into the soil. These substances may penetrate all plant organs and consequently contribute to toxic contamination of food of plant origin. The degree of contamination depends on factors such as, including the dose and frequency of applications, physicochemical properties of the active substance, formulation type, crop species, soil characteristics, and weather conditions [2].

The presence of pesticide residues in food is one of the key indicators of food safety. Long-term consumption of contaminated products may lead to bioaccumulation in the human body, potentially increasing health risks. Pesticides can cause mutagenic, teratogenic and carcinogenic effects. They disrupt hormonal and enzymatic systems and may contribute to respiratory, digestive, lymphatic, and skin diseases. Some pesticides are embryotoxic and may impair reproduction and foetal development [3–7].

Globally, it is estimated that 64% of agricultural land (approximately 24.5 million km^2) is exposed to contamination with more than one active pesticide substance, and 31% is

✉ Address for correspondence: Magdalena Florek-Łuszczki, Department of Medical Anthropology, Institute of Rural Health, Jaczewskiego 2, 20-090 Lublin, Poland
E-mail: magdalena.florek@wp.pl

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Table 1. Cultivation area and production of berry fruits (strawberry, raspberry, blueberry) in Poland, 2021–2024

Fruits	Area (thousand ha)				Production (thousand tons)			
	2021	2022	2023	2024	2021	2022	2023	2024
Berry fruits	130.2	131.2	129.6	126.3	558.4	590.2	555.0	472.1
Strawberry	3.7	31.0	29.7	28.9	155.9	185.1	179.7	158.6
Raspberry	19.8	21.7	21.4	19.3	103.9	104.9	96.1	76.9
American blueberry	10.7	11.4	12.4	12.5	55.3	64.0	61.9	62.0

Source: authors' own elaboration based on 2024 data from the Institute of Agricultural and Food Economics – National Research Institute (IERiGŻ PIB) [9]

considered at high risk. Of the high-risk areas, 34% are located in biodiversity hotspots, 5% in regions suffering from water scarcity, and 19% in low- and lower-middle-income countries [8].

Berry fruits are an economically important crop in Poland, accounting for 36.8% of the fruit cultivation area and 11.2% of total fruit production in 2024 (Tab. 1) [9]. There is, and will continue to be, a high demand for strawberries, raspberries and blueberries due to their dietary value. In general, they are well known for their nutritional content, including minerals, vitamins, fatty acids, and dietary fibre. These fruits are rich in compounds that prevent cancer, and also have a high antioxidant capacity, offering significant health benefits for humans. For this reason, the consumption of both fresh fruits and their processed products is on the rise [10, 11].

Berry fruits available on the market should not contain pesticide residues at levels exceeding the current maximum residue levels (MRLs), and any case of exceedance should be subject to risk assessment. Activities aimed at protecting consumer health related to the consumption of food contaminated with pesticides should be based on thorough scientific research and professional risk analysis. Despite the introduction of rules for the use of plant protection products in crop protection, the monitoring programme and official control, studies on the assessment of health risks resulting from the accumulation of these substances in the human body, remain relevant [3].

MATERIALS AND METHOD

For health risk assessment, data from the report of the National Institute of Public Health – National Institute of Hygiene – National Research Institute (NIZP PZH-PIB) [12] in Warsaw were used. The health risk assessment of exposure to pesticide residues in the analysed berry fruits was carried out for selected consumer groups, based on acceptable intake levels per kilogram of body weight. Exposure was assessed for consumers after consumption of fruit with known concentrations of identified pesticides. Average daily consumption was assumed according to available literaturę data. The applied risk assessment methodology is commonly used in similar studies [13, 14].

The average concentration of pesticides detected in samples of selected berry fruits available on the domestic market included in the NIZP PZH-PIB report as part of the official control conducted in Poland is shown in Table 2 [12].

Table 3 presents the average daily consumption of selected berries (critical diet in bold italics) in Poland in 2022 according to the NIZP-PZH report. [12].

Health risks associated with the consumption of residues of selected plant protection products (pesticides) in the assessed berry fruits were determined based on the following indicators [13, 15]:
– safe value of estimated daily intake (EDI);
– hazard quotient (HQ);
– health risk (Hazard Index, HI).

Table 2. Mean concentration and 95th percentile of pesticide residues most frequently detected in berry fruit samples in Poland in 2022, according to the NIZP-PZH Report

Pesticide	Mean concentration [mg kg^{-1}]	P95 [mg kg^{-1}]	MRL value in force in 2022 [mg kg^{-1}]
Strawberry			
Fluopyram	0.023	0.120	2
Cyprodynil	0.026	0.135	5
Boscalid	0.018	0.044	6
Raspberry			
Cyprodynil	0.071	0.040	3
Fludioxonil	0.250	0.139	5
American blueberry			
Boscalid	0.039	0.241	15
Cyprodynil	0.031	0.178	8
Fludioxonil	0.051	0.151	4
Acetamiprid	0.030	0.056	2

Source: based on the report Analysis of potential consumer health risks from pesticide residues in foods available on the Polish market in 2022 [12]

The daily intake of a given contaminant (EDI) depends both on the concentration of individual contaminants in fruits and on their daily consumption. EDI (in mg per kg of fruit per day) was calculated as follows [15]:

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

where:
– C (mg × kg^{-1}) – the average concentration of the given contaminant in the collected fruit samples;
– C_{on} (kg × person^{-1} × d^{-1}) – the daily average consumption of fruits;
– BW (kg person^{-1}) – represents body weight 62.8 kg [12].

The non-carcinogenic risk for an adult consumer resulting from the consumption of selected fruits was estimated using the following equation:

$$HQ = EDI/ADI \qquad (2)$$

where:
– HQ is the value of pesticides [15];
– ADI was obtained from the NIZP-PZH Report [12].

Table 3. Average daily consumption of selected berry fruits (critical diet highlighted in bold italics) in Poland in 2022 according to the NIZP-PZH Report

Strawberry			
Diet	Average body weight [kg]	Daily consumption [g kg^{-1} b.w. day^{-1}]	Daily consumption [g person^{-1} day^{-1}]
Child			
DE child	***16.15***	***0.5000***	***8.0750***
UK infant	8.70	0.2184	1.9000
UK toddler	14.60	0.1986	2.9000
Adults			
PL general population	62.80	0.0191	1.2000
UK adult	76.00	0.0474	3.6000
UK adult vegetarian	66.70	0.0750	5.0000
GEMS/Food G08	60.00	0.0943	5.6600
DE general population	76.37	0.1090	8.3232
DE females aged 14–50 years	67.47	0.1191	8.0344
Raspberry			
Diet	Average body weight [kg]	Daily consumption [g kg^{-1} b.w. day^{-1}]	Daily consumption [g person^{-1} day^{-1}]
Child			
DE Child	16.15	0.0600	0.9690
UK infant	8.70	no data	no data
UK toddler	14.60	0.1027	1.5000
FI child 3 years	***15.20***	***0.185***	***2.8195***
Adults			
PL general population	62.80	0.0080	0.5000
UK adult	76.00	0.0066	0.5000
UK adult vegetarian	66.70	0.0090	0.6000
GEMS/Food G08	60.00	0.0152	0.9100
DE general population	76.37	0.0223	1.6995
DE females aged 14–50 years	67.47	0.0253	1.7061
American blueberry			
Diet	Average body weight [kg]	Daily consumption [g kg^{-1} b.w. day^{-1}]	Daily consumption [g person^{-1} day^{-1}]
Child			
DE Child	16.15	0.0200	0.3230
UK infant	8.70	no data	no data
UK toddler	14.60	no data	no data
NL toddler	***10.20***	***0.0310***	***0.3162***
Adults			
PL general population	62.80	0.0032	0.2000
UK adult	76.00	no data	no data
UK adult vegetarian	66.70	no data	no data
GEMS/Food G08	60.00	0.0038	0.2300
DE general population	76.37	0.0122	0.9297
DE females aged 14–50 years	67.47	0.0128	0.8608

Source: based on FAO/WHO GEMS/Food Cluster Diet G06 2012 (WHO 2012)

The measure of the potential risk of adverse health effects caused by a mixture of chemical substances is the hazard index (HI). This coefficient is used in most analyses to assess the risk of mixtures. The HI for the average daily consumption of vegetables was calculated as follows:

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

HQ has been recognized as one of the main parameters for assessing the non-carcinogenic risk associated with the consumption of contaminated food [15]. The HQ values for pesticides were calculated (Tab. 4). If the HQ value is less than 1, it is unlikely that individuals are exposed to a toxic level of a given contaminant in food products, which could consequently harm human health [15].

Table 4. Values of EDI and HQ and MRL for residues of selected active substances in berry fruits consumed by adults (A) and children (Ch)

Berry fruits	EDI		HQ		MRL
	Pesticide active substance				
	A	Ch	A	Ch	2.0
Strawberry	Fluopyram				
	2.51×10^{-6}	1.15×10^{-5}	2.09×10^{-5}	9.58 ×10^{-4}	
	Cyprodynil				5.0
	2.83×10^{-6}	1.30×10^{-5}	9.45×10^{-5}	4.33×10^{-4}	
	Boscalid				6.0
	1.96×10^{-6}	9.00×10^{-6}	4.91×10^{-5}	2.25×10^{-4}	
Raspberry	Cyprodinil				3.0
	1.58×10^{-6}	4.26×10^{-6}	5.28×10^{-5}	1.42×10^{-4}	
	Fludioxonil				5.0
	5.58×10^{-6}	1.50×10^{-5}	1.51×10^{-5}	4.05×10^{-5}	
American blueberry	Boscalid				15.0
	4.76×10^{-7}	7.80×10^{-6}	1.19×10^{-5}	1.95×10^{-5}	
	Cyprodinil				5
	3.78×10^{-7}	6.20×10^{-7}	1.26×10^{-5}	2.07×10^{-5}	
	Fludioxonil				4.0
	6.22×10^{-7}	1.02×10^{-6}	1.68×10^{-6}	2.76×10^{-6}	
	Acetamiprid				0.7
	7.66×10^{-7}	6.00×10^{-7}	7.32×10^{-5}	1.20×10^{-4}	

Source: Own study based on European Commission data on pesticide residues and maximum residue levels (mg/kg) in 2025

Environmental risk assessment. When assessing food safety in terms of pesticide residues, it is equally important to consider environmental risks. Pesticides used in the cultivation of berry fruits such as strawberries, raspberries and blueberries, may disperse beyond the target crop ecosystem, contaminating soil and water and affecting non-target organisms. Even if residue levels in fruits remain well below the maximum residue limits (MRLs), these substances may accumulate in the environment, form mixtures, and cause effects that are difficult to predict. After application, pesticides undergo physicochemical and biological processes, such as soil adsorption, leaching into groundwater, surface runoff, and biodegradation. The properties of a given compound – water solubility, organic carbon partition coefficient (Koc), and half-life (DT50) – determine its mobility and persistence in the environment.

Boscalid and *Fluopyram*, for example, are fungicides with relatively long degradation times in soil (DT50 exceeding

100 days), indicating high persistence. Their residues may accumulate in the plough layer and gradually leach into groundwater.

Acetamiprid, a neonicotinoid insecticide, shows moderate persistence but high water solubility, which increases the risk of migration into aquatic ecosystems.

Cyprodinil and *Fludioxonil* also display moderate mobility, and their residues have been detected in orchard soils in Europe.

Aquatic organisms such as fish, crustaceans, and benthic invertebrates are particularly sensitive to pesticide contamination. Acute toxicity indicators, such as LC50 (lethal concentration for 50% of the population) and EC50 (sublethal effect in 50% of organisms), are commonly used in environmental risk assessments. Fluopyram and boscalid may be toxic to water fleas (*Daphnia magna*), with EC50 values in the low mg/L range. Acetamiprid, despite relatively faster degradation in water, exhibits high toxicity to aquatic insects and to fish at early developmental stages. Monitoring studies in Europe suggest that for certain pesticides, especially neonicotinoids, RQ values may exceed the safety threshold in rivers and streams located near intensively managed berry plantations. One of the most widely discussed environmental concerns associated with pesticide use is their impact on pollinators, primarily the honeybee (*Apis mellifera*) and bumblebees (*Bombus* spp.). Although acetamiprid is considered less toxic than other neonicotinoids (e.g. imidacloprid or clothianidin), it still exerts sublethal effects – interfering with spatial orientation, learning ability, and foraging activity of pollinators. Fungicides such as boscalid and fludioxonil, although not highly toxic to bees on their own, may act synergistically with insecticides, thereby increasing harmful impacts [8, 16–19].

The basic method for assessing the environmental risk of pesticides is the analysis of the Risk Quotient (RQ) indicator [16]:

$$RQ = PEC/ PNEC$$

where:
– PEC -Predicted Environmental Concentration;
– PNEC -Predicted No-Effect Concentration.

Interpretation of RQ values is as follows:
– RQ < 0.1 – negligible risk;
– 0.1 ≤ RQ < 1 – moderate risk;
– RQ ≥ 1 – potential environmental risk, requiring mitigation/management actions.

Monitoring data from Europe indicate that for some pesticides used in berry cultivation, e.g., acetamiprid, RQ values for pollinators may periodically exceed 1, particularly in intensive production systems.

To evaluate potential risks of pesticide residues for terrestrial ecosystems, a screening-level environmental risk assessment was carried out. Predicted no-effect concentrations for soil organisms (PNEC_soil) were derived from the lowest available chronic NOEC (No Observed Effect Concentration) values for relevant soil taxa (earthworms, collembolans), obtained from EFSA dossiers and the Pesticide Properties Database (PPDB), applying an assessment factor (AF) of 10 in accordance with the EU Technical Guidance Document [17, 18]. Risk quotients (RQ) were then calculated according to the equation [16]:

$$RQ=MEC/ PNEC$$

where:
– MEC -represents the measured (or assumed) environmental concentration in soil.

Since no Polish monitoring data for these compounds were available, two conservative screening scenarios were applied: MEC = 0.01 mg/kg and MEC = 0.10 mg/kg dry soil [20].

The obtained results of the PNECsoil and RQ assessment for pesticides in berry crops are presented in Table 5.

At the lower level scenario (MEC = 0.01 mg/kg), all pesticides showed RQ < 0.4, with acetamiprid being the highest (0.37). This indicates a low environmental risk at this contamination level. At the higher level scenario (MEC = 0.10 mg/kg), fungicides, such as boscalid, cyprodinil, fludioxonil and fluopyram, remained below the risk threshold (RQ < 1), although boscalid approached the limit (0.84 – moderate risk). Acetamiprid exceeded the risk threshold at MEC = 0.10 mg/kg (RQ = 3.70), signalling potential ecological concern for soil invertebrates, especially collembolans. These findings indicate that while most fungicides pose little-to-no chronic risk to terrestrial organisms at realistic soil concentrations, neonicotinoid insecticides, such as acetamiprid, may require closer attention. Due to its relatively low NOEC for collembolans, even moderate soil contamination could lead to ecological risks.

RESULTS AND DISCUSSION

In the present analysis of consumer exposure to pesticide residues in berry fruits available in Poland in 2022, strawberries, raspberries, and blueberries were considered. Estimated daily intake (EDI) values and hazard quotients (HQ) were calculated separately for children and adults, using data on mean pesticide concentrations in fruits and levels of consumption (Tab. 4).

In all analysed cases, HQ values remained well below the reference threshold of 1, indicating no risk of chronic

Table 5. $PNEC_{soil}$ values and RQ for berry crop pesticides under two screening scenarios

Pesticide	Lowest chronic NOEC[1] 1 (soil taxa) [mg/kg]	PNEC soil [mg/kg]	RQ at MEC = 0.01 mg/kg	RQ at MEC = 0.10 mg/kg	Source of NOEC
Acetamiprid	0.27 (Collembola *F. candida*)	0.027	0.37	3.70	PPDB/EFSA[2]
Boscalid	1.197 (*E. fetida*)	0.120	0.08	0.84	PPDB/EFSA
Cyprodinil	6.7 (*E. fetida*)	0.67	0.01	0.15	PPDB/EFSA
Fludioxonil					
Fluopyram					

[1] No Observed Effect Concentration.
[2] The Pesticide Properties DataBase (PPDB). Agriculture & Environment Research Unit (AERU), University of Hertfordshire, Hatfield, UK.

health exposure in the studied populations. The highest HQ values were observed for fluopyram in strawberries and acetamiprid in blueberries. Although these values were the highest in the dataset, they were still more than three orders of magnitude lower than the reference levels, which means that no significant health risk to consumers was identified.

Other pesticides showed even lower HQ values. For boscalid, the highest HQ was found in strawberries consumed by children, while the lowest was in blueberries consumed by adults. Fludioxonil was characterised by particularly low HQ values. These results indicate that in 2022, none of the analysed substances posed a threat in the context of chronic exposure, even when multi-residue contamination was considered.

A comparative analysis between age groups showed that HQ values for children were clearly higher than for adults. This results from the higher fruit consumption per body weight in children, which leads to proportionally higher pesticide intake. These differences were particularly evident in the case of strawberries, which are an important element of children's diet. HQ values for children were up to four times higher than for adults, although they remained far below the reference threshold.

The environmental risk assessment carried out in this study, although screening-level in nature, revealed notable differences in the potential impacts of individual active substances used in berry production. The analysis was based on PNEC values derived from the lowest chronic NOECs for soil organisms (earthworms, collembolans), applying an assessment factor of 10, and compared against two conservative soil contamination scenarios (MEC = 0.01 mg/kg and 0.10 mg/kg). The results indicate that most fungicides, including boscalid, cyprodinil, fludioxonil and fluopyram, exhibited low risk quotients (RQ < 1), even under the higher contamination scenario, suggesting limited chronic risks for soil biota under typical agricultural use. However, boscalid showed RQ values approaching 1 in the higher MEC scenario, which may point to the potential for sublethal effects, especially in cases of repeated applications and accumulation in soil (Tab. 5).

The most critical results were observed for acetamiprid, a neonicotinoid insecticide, which exceeded the safety threshold (RQ > 1) at MEC = 0.10 mg/kg. This finding highlights a potential ecological risk for sensitive soil invertebrates, particularly collembolans, which are highly susceptible to this compound in ecotoxicological studies. These outcomes are consistent with the broader literature, where neonicotinoids have frequently been identified as particularly hazardous to both soil invertebrates and pollinators [17, 20, 21]. The accumulation of acetamiprid residues in soil may lead to chronic exposure of non-target organisms, thereby affecting ecosystem processes such as organic matter decomposition and nutrient cycling [16, 17, 19–22].

It should also be noted that boscalid and fluopyram are characterized by relatively high soil persistence (DT_{50} often exceeding several weeks), increasing the likelihood of accumulation in agricultural soils under intensive cultivation practices. In contrast, fungicides with shorter half-lives, such as cyprodinil and fludioxonil, appear to pose a lower long-term risk, although repeated applications may also contribute to local buildup [23]. This analysis underscores the need for further empirical measurements of soil concentrations in berry plantations, as the assumed MEC values may either under- or over-estimate real environmental levels.

The present assessment suggests that although the overall environmental risk to soil from most pesticides applied in berry cultivation in Poland appears to be limited, acetamiprid emerges as a compound of particular concern. This insecticide should therefore be prioritised in future monitoring and ecotoxicological studies, especially concerning its effects on sensitive soil invertebrates, and its potential to contribute to long-term changes in soil ecosystem functioning. Integrating soil monitoring data with multi-residue analysis and including indicator species in further studies will help to better characterise the long-term effects of pesticide residues on soil ecosystems and biodiversity.

The results of the present study are consistent with findings reported in other countries. As reported by Keklik et al., among 245 analysed strawberry samples, 61.6% contained 32 different pesticides (17 fungicides and 15 insecticides), five of which were not approved. Moreover, 6.5% of strawberry samples exceeded the maximum residue limits (MRLs) established by the European Union. In 42.9% of samples, multiple pesticide residues were detected. The most frequently identified pesticide was pyrimethanil (30.2%), followed by boscalid (27.4%), fluopyram (17.1%), and bifenazate (15.1%). In the worst-case scenario, cumulative exposure to pesticides through strawberry consumption was estimated at 6.5×10^{-5} mg kg^{-1} b.w. day^{-1} for adults and 2.0×10^{-4} mg kg^{-1} b.w. day^{-1} for children, with hazard index (HI) values of 0.32% and 0.97%, respectively. These results suggest that there are no concerns regarding cumulative exposure to residues from strawberry consumption among the Turkish population [24].

Similarly, research conducted by Li et al., focusing on 142 pesticide residues in 245 strawberry samples, showed that 26.0% of samples contained at least one pesticide residue, with four samples exceeding the MRLs established in China. Carbendazim, pyrimethanil, and azoxystrobin were the most frequently detected pesticides in strawberry samples. In the worst-case scenario, HI values for adults and children were 0.91% and 3.62%, respectively, and carbofuran, bifenazate, and pyraclostrobin were identified as the three main contributors to the HI [25].

In a study conducted by Sadło et al. on the 'Laszka' dessert raspberry cultivar plantation in Grabówka Kolonia, Lublin Province in eastern Poland, a total of 40 raspberry samples were analysed for residues of folpet, tetraconazole, pyrimethanil, boscalid, pyraclostrobin, cyprodinil, azoxystrobin, and difenoconazole (fungicides), as well as chlorpyrifos, λ-cyhalothrin, pirimicarb, and cypermethrin (insecticides). Residues of boscalid and pyraclostrobin (2.395 mg/kg and 0.732 mg/kg, respectively) corresponded to approximately 24% of their MRLs, while cypermethrin (0.235 mg/kg) reached nearly 50% of its MRL. Long-term intake of these substances by adult Polish consumers was also low, accounting for 0.52%, 0.22%, and 0.04% of ADI, respectively. These results indicated that even on the harvest day of ripe raspberries, pesticide residues were well below their respective MRLs, and their daily intake did not approach 1% of ADI [26].

Monitoring of pesticide residues in raspberries from the 2021 harvest in Serbia focused on detecting residues in organic cultivation. Among 40 analysed samples, 32.5% were contaminated with pesticide residues, of which 12.5% were below the MRLs, and 20% exceeded the MRLs [27].

Milinčić et al. investigated the bioavailability of pesticide residues in blueberries from Serbia, considering the complex food matrix, and assessed the potential health risk to humans. Pesticide residues detected in the study were below the MRL values. Exposure to pesticide residues was very low, in all cases below 0.01% of ADI. The highest exposure was observed for boscalid, and the lowest for fludioxonil, across all subpopulations. For adults and adolescents, HQ ranged from 0.000006% – 0.002% of ADI, while for children, preschoolers, and infants, HQ ranged from 0.00001% – 0.008% of ADI. Cumulative exposure (HI) ranged from 0.00004% for adults to 0.012% for infants. The chronic risk assessment showed that the risk is acceptable for the health of different human subpopulations [28].

Limitation of the study. Actual consumer exposure associated with the consumption of berries contaminated with pesticide residues may lead to an over- or under-estimation of actual exposure. This is because the health risk assessment method used in the study is based on simplified assumptions about the same consumers. Interpretation of the results should take this limitation into account, and the estimated indicators should be considered preliminary.

CONCLUSIONS

1) All calculated values of estimated daily intake (EDI), hazard quotients (HQ) and hazard index (HI) for pesticide residues in strawberries, raspberries and blueberries consumed in Poland in 2022, were far below the reference limit (HQ < 1; HI < 0.001), indicating no chronic health risk for either adults or children, despite higher exposure estimates in the latter group.
2) The environmental risk assessment based on risk quotients (RQ) showed that most pesticides detected in berries are unlikely to pose a threat to aquatic or terrestrial organisms under typical exposure conditions.
3) Acetamiprid was identified as the most critical substance in the soil compartment: at a conservative MEC of 0.10 mg/kg, RQ values exceeded 1, indicating a potential ecological risk for sensitive soil invertebrates, particularly collembolans, and a higher concern compared with other pesticides.

The obtained results highlight the importance of integrating human health and environmental endpoints in pesticide risk assessment, with particular attention to substances of high ecotoxicological concern and to vulnerable populations such as children and pollinators. It is therefore recommended that national monitoring of pesticide residues in both food and agricultural soils should be continued as a key element of sustainable agriculture and public health protection, with special focus on compounds with low ADI values and on sensitive population groups. Future studies should also refine the assumptions used in this assessment and incorporate more detailed exposure data (e.g., distributions of concentrations and consumption) to provide a more comprehensive and nuanced evaluation of both health and environmental risks.

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