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Effect of consumption of vegetables contaminated with pesticides on consumers' health – risk analysis

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Abstract

Introduction and Objective. The presence of pesticide residues in food is the consequence of the use of conventional methods of plant protection. The aim of the study was to assess health risk after consumption of the edible parts of vegetables (carrots, cucumbers, tomatoes) contaminated with pesticides.

Materials and Method. Research material was based on the results of pesticide residues in food available on the Polish market during 2019–2023. The volume of consumption of selected vegetables for the purposes of assessment of health risk was determined based on data from literature. In turn, data concerning the intake of daily doses of residues of harmful compounds after consumption of the selected vegetables were taken into account as part of the official control and monitoring carried out by the Chief Sanitary Inspectorate (GIS) reported by the National Institute of Public Health of the National Institute of Hygiene – National Research Institute (NIZP-PZH), and data from literature.

Results. The calculated HI value indicates that no risk of occurrence of adverse health effects for consumers' health should be expected, caused by the mixture of chemical substances after consumption of the analyzed vegetables.

Conclusions. Contamination of plant foods with pesticides creates a serious risk for human health. Strict control of food is recommended starting with primary production through processing, storage, distribution, ending with consumption. To limit health risk resulting from exposure to pesticide residues while consuming vegetables, precautionary measures should be taken based on the application of good agricultural practices. The assessment of health risk caused by exposure to pesticides should be a permanent element of the activities of institutions responsible for food safety 'from farm to fork', especially those responsible for public health.

Key words

tomato, pesticide residues, carrots, cucumbers, consumption standards, assessment of health risk

INTRODUCTION

The adverse effect of pollution of the environment on food safety is a serious problem worldwide. The quality of currently produced plant raw materials is becoming an important issue in conditions of global competition [1, 2]. The relationship between diet and health indicates that daily diet may significantly modify the health responses of the body. This situation is disturbed by the fact that in the products consumed, chemical substances, including pesticides, are present which may create a potential risk for the health and life of consumers [3, 4]. Products of plant origin are an important element of the daily human food ration. Due to the high consumption of food products they significantly contribute to the daily intake of hazardous chemical compounds. Considering the toxicity of chemical compounds (pesticides) in products of plant origin their content should be assessed [5].

Human exposure to pesticides may also occur through environmental pathways, such as water, soil, or air [6].

Cumulative Risk Assessment (CRA) is an approach that integrates the impact of simultaneous exposure to multiple chemical substances that may affect the human body through common or similar toxicological mechanisms. In the context of pesticide residues in food, this concept allows for a more realistic assessment of potential hazards, taking into account situations in which consumers are simultaneously exposed to trace amounts of multiple compounds with additive or synergistic effects [7].

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In traditional risk assessments, pesticides are typically evaluated individually-based on their Acceptable Daily Intakes (ADI) or Acute Reference Doses (ARfD). However, the cumulative approach assumes that even low levels of multiple pesticides – acting through similar toxicological pathways – may together produce significant health effects. Incorporating the CRA concept into food safety assessments enables the identification of potentially underestimated risks arising from the concurrent presence of multiple pesticide residues in the diet. This represents an important step toward integrated and preventive public health protection, aligning with the recommendations of agencies such as the European Food Safety Authority (EFSA) and the US Environmental Protection Agency (US EPA) [8]. Traditional risk assessment approaches most often consider the effects of individual chemical substances in isolation, without accounting for real-world exposure scenarios, which are typically complex and involve multiple compounds. Modern approaches to health risk assessment related to chemical contamination in food and the environment increasingly focus not only on individual substances, but also on mixtures that occur together and may interact. In the case of pesticides – which often appear in food as multi-residue combinations – the concept of cumulative risk assessment (CRA), focusing on substances with similar toxicological modes of action, is particularly important. At the same time, there is growing evidence that pesticides may interact with other environmental contaminants, such as heavy metals (e.g., cadmium, lead, mercury), which can lead to synergistic or additive toxic effects, significantly increasing the risk to human health [9, 10].

The relationship between diet and health indicates that the daily diet may significantly modify health responses of the body; proper nutrition is the key element in the treatment of many diet-related diseases [11]. This situation may be disturbed by the fact that food products may contain chemical substances which may create a potential risk for the health and life of consumers. The identification of the threat areas in the whole food chain, i.e. from primary production through processing, storage and distribution of food products, ending with consumption, is the basis for ensuring food safety [3, 4, 5].

The presence of pesticide residues in vegetables is considered to be one of the main problems in food safety. This is confirmed by annual reports by the European Union (EU) and EFSA on the monitoring of the occurrence of residues of pesticides in food. The report by the EFSA 2022 showed that among all samples examined as many as 40.3% were contaminated with pesticides, including 5.1% of samples which exceeded the maximum allowable value of the content of pesticides in food, or in animal feed.

The content of pesticide residues in food is expressed in milligrams per kilogram (MRL[1]) [12]. Table 1 presents data from the EFSA monitoring concerning pesticide residues in food during 2016–2020.

According to the legal regulations in Poland, food safety and nutrition is managed within the network of the Rapid Alert System for Food and Feed (RASFF) by the Chief Sanitary Inspector (GIS), who reports detected cases of hazardous food and feed to the European Commission (EC) (Tab. 2) [13].

[1] MRL – 'maximum residue level' is defined as the highest legally allowable level of the concentration of residue levels of pesticides in or on food and feed, established in accordance with the Regulation (EC) No 396/2005, based on good agricultural practice and the lowest exposure of consumers, which is indispensable for protection of human health

Table 1. Data from EFSA monitoring concerning pesticide residues in food (2016–2020)

Year	Number of samples examined	Samples containing pesticide residues exceeding allowable reference limit	Number of organic samples examined (% of a total number of samples examined)	Organic samples containing pesticide residues below MRL[1]	Samples containing pesticide residues below MRL	Organic samples containing pesticide residues exceeding allowable reference limit
2016	84 657	45.5%	3.8%	5495 (6.5%)	15.6%	1.3%
2017	88 247	41.8%	4.1%	5806 (6.6%)	13.7%	1.5%
2018	91 015	43.3%	4.5%	5735 (6.3%)	15.2%	1.4%
2019	96 302	39.5%	3.9%	6048 (6.2%)	13.1%	1.3%
2020	88,141	40.3%	5.1%	5783 (6.5%)	19.9%	1.5%

Source: Own compilation based on data by the EFSA 2020 [12]

Table 2. Reports to the RASFF by the GIS concerning pesticide residues in food during 2019–2023 [13]

No. of reports	Year				
	2019	2020	2021	2022	2023
	0	17	41	42	63

Source: own compilation based on data included in the activity reports by the GIS

As demonstrated by the report of the National Institute of Public Health of the National Institute of Hygiene – National Research Institute (NIZP-PZH) [14], in 2020, a total number of 3,246 (100%) food samples were examined for pesticide residues within official control and monitoring carried out by the GIS. The examinations covered a total number of 335 chemical compounds – pesticide residues. In 1,558 samples, i.e. 48.0%, the presence of at least one pesticide was found at a level not exceeding the highest allowable values of pesticides (MRL). No pesticide residues were detected in 1,504 (46.33%) samples, whereas in 184 samples, i.e. 5.6%, the maximum residue level was exceeded for at least one pesticide. In 2020, the pesticides most often detected were fungicides: boscalid, fluopyram, captan, fludioxonil, imazalil, azoxystrobin, cyprodinil), and an insecticide – acetamiprid [14].

Taking into account exposure scales and possible health effects associated with the consumption of vegetables contaminated with pesticides, the size of crop, amount and type of plant protection products used, should be considered with regard to the conducted official control which does not cover 100% of crops. Therefore, the assessment of health risk based on available data and the related prevention is such an important element of food safety.

While assessing health risk it is necessary to analyze many factors which exert an effect on the contamination of food with hazardous substances originating from sewage discharge, illegal waste dumps and their fires, industrial emissions, inappropriate use of agrochemicals and mineral fertilizers, and from improper storage and contamination at points of sale. At present, environmental pollution is a global public health problem which exerts an effect on the quality of soil and, consequently, decides about the quality of the food produced, potentially contaminated, resulting in a negative effect on human health [2,4].

In recent years, special attention has been paid to the protective effect of diet and its various components on human functioning throughout the entire lifespan. In this

Table 3. Mean monthly and daily consumption of selected food products per person in households, according to socio-economic groups in Poland in 2023 [15]

Specification [in kg]	Total	Households of							
		employees			farmers	the self-employed	retirees and pensioners		
		total	in				total	retirees	pensioners
			manual labour positions	nonmanual labour positions					
Bread and cereals: monthly	6.830	6.260	6.280	6.240	6.800	6.090	8.820	8.850	8.480
daily	0.224	0.205	0.206	0.205	0.223	0.200	0.289	0.290	0.278
Carrots monthly	0.370	0.330	0.320	0.340	0.390	0.330	0.490	0.490	0.510
daily	0.012	0.010	0.010	0.011	0.012	0.010	0.016	0.016	0.016
Cucumbers monthly	0.420	0.380	0.400	0.370	0.510	0.360	0.520	0.530	0.470
daily	0.013	0.012	0.013	0.012	0.016	0.011	0.017	0.017	0.015
Tomatoes monthly	0.700	0.660	0.610	0.690	0.580	0.670	0.890	0.900	0.810
daily	0.023	0.021	0.020	0.022	0.019	0.022	0.029	0.029	0.026

Source: own compilation based on data by the GUS. Household budgets in 2023 [15]

respect, vegetables are of special importance considering their confirmed beneficial effect on health. Taking care of one's health, which includes proper nutrition, is not only an individual approach of the consumer, but is also primarily of public importance because the mode of nutrition exerts a strong effect on public health, social, as well as the economic life of the country [6, 11].

Table 3 presents the size of a mean monthly and daily consumption of selected vegetables per person in households, according to socio-economic groups in Poland in 2023 [15].

In food production it is important to implement and develop food safety management systems, the primary goal of which is to ensure the safety, health and life of the consumer. At all stages of the food chain it is important to eliminate threats through risk analysis-based tools. The approach to the problem of threat based on risk analysis is a significant change in the provision of food safety and, consequently, exerts an effect on the improvement of the state of health of consumers. Food safety and improving preventive public health activities are basic goals in the system of complex health care of the general population. Therefore, it is necessary to undertake actions which would limit the possibility of introducing into circulation on the market food that poses a threat to the health or life of consumers. This is the reason for conducting health risk assessment [5].

Possible health effects. The use of pesticides in agriculture results in their residues in agri-food products and, therefore, constitutes a real threat to the health of consumers. The effects of consumption of pesticides and their negative effect on human health in the form of various chronic diseases have been already discussed in earlier studies (literature). Some studies emphasize the cumulative effect of consumption of contaminated food which is associated with the presence of pesticide residues exceeding the allowable limit specified by the World Health Organization (WHO). According to literature, chronic exposure, even to low levels of some pesticides, may cause memory problems or even memory loss, as well as behavioural problems in children, as well as loss of coordination, decreased speed of response to stimuli, reduced ability to see, altered or uncontrolled mood, and general weakness. In addition, this may lead to defects in the reproductive system (endometriosis, uterine fibroids)), inhibition of blood clotting, paralysis of the respiratory and circulatory systems, arterial hypertension and even cancer [16–19].

The presence of many pesticide residues in food carries health risk for consumers due to their high toxicity [20]. Mixtures of compounds with a common mechanism of action, at low concentrations of co-occurring substances, create the probability of additive action [21].

MATERIALS AND METHOD

The assessment of health risk resulting from exposure to residues of plant protection products in the analyzed vegetables was performed in relation to the selected groups of consumers, based on allowable limits of consumption per kilogram body weight. The exposure of consumers after consuming vegetables with a known content of identified pesticides was considered. The mean daily vegetable consumption was assumed based on available data from literature. Tables 4, 5 and 6 demonstrate data included in the risk assessment [14].

Samples for testing compliance with maximum residue levels (MRLs) were collected as part of both the coordinated EU and national food monitoring and official control programmes by staff of the State Sanitary Inspection, following the relevant legal regulations. In the risk assessment of pesticide residues in vegetables, the calculations did not take into account reduction factors that may reflect potential decreases in residue levels due to peeling, washing, cooking, or other processing methods. The study assesses the pesticide active substances that were most frequently detected in official food control and monitoring programmes. The data refer to raw vegetables, and take into account both children and adult populations [14].

Table 4. Estimated daily intake (EDI) expressed as percentage of acceptable daily intake (ADI) of the selected vegetables in accordance with the report by the NIZP-PZH [14]

Pesticide	Carrots									
Boscalid ADI 0.04 mg kg^{-1} b.w./ day^{-1} EFSA 2013	DE child	UK infant	UK small child	*DK child*[1]	PL general	UK adult	UK adult vegetarian	GEMS/Food G08	DE general	DW females aged 14–50
Mean	0.02%	0.03%	0.01%	*0.03%*	0.01%	0.00%	0.01%	0.01%	0.01%	0.01%
P95	0.08%	0.11%	0.06%	*0.11%*	0.02%	0.01%	0.02%	0.04%	0.02%	0.02%
	Cucumbers									
PROPAMOCARB ADI 0.24 mg kg^{-1} b.w./day^{-1} EFSA 2006, 2013	DE child	UK infant	UK small child	*DK child*	PL general	UK adult	UK adult vegetarian	GEMS/Food G08	DE general	DW females aged 14–50
Mean	0.05%	-	0.01%	*0.14%*	0.01%	0.01%	0.01%	0.02%	0.01%	*0.02%*
P95	0.24%	-	0.04%	*0.66%*	0.03%	0.02%	0.04%	0.07%	0.07%	*0.08%*
FLUOPYRAM ADI 0.12 mg kg^{-1} b.w./day^{-1} EFSA 2013	Tomatoes									
	DE child	UK infant	UK small child	PL general	UK adult	UK adult vegetarian	GEMS/Food G08	DE general	DW females aged 14–50	*GE MS/Food G06*
Mean	0.08%	0.03%	0.05%	0.07%	0.03%	0.05%	0.09%	0.05%	0.06%	*0.28%*
P95	0.26%	0.10%	0.16%	0.24%	0.12%	0.17%	0.30%	0.18%	0.20%	*0.95%*

Source: Report by the NIZP-PZH 2020 [14]
[1] results for the critical diet are in italic

Table 5. Mean concentration and 95. percentile of the concentration of pesticides detected in the selected vegetables according to the report by the NIZP-PZH [14]

Pesticide	Mean concentration [mg kg^{-1}]	P95 [mg kg^{-1}]	MRL value applicable in 2020 [mg kg^{-1}]
	Carrots		
Boscalid	0.009	0.032	2.0
	Cucumbers		
Propamocarb	0.208	0.973	5.0
Fluopicolide	0.019	0.072	0.5
Fluopyram	0.026	0.096	0.5
	Tomatoes		
Fluopyram	0.009	0.032	0.9

Source: Report by the NIZP-PZH 2020 [14]

RESULTS AND DISCUSSION

Health risk related with the consumption of residues of the selected active substances of pesticides in the assessed vegetables specified, based on the following indicators:
- safe value of estimated daily intake (EDI);,
- target threat quotient (THQ);
- hazard index (HI).

The daily consumption of a given contaminant (EDI) depends both on the concentration of individual contaminants in vegetables, and their daily intake. EDI (*in micrograms per kilogram of vegetable per day*) was calculated as follows:

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

where:
- C (μg kg^{-1}) – *the mean concentration of a given contaminant in the collected vegetable sample;*
- C_{on} (kg $person^{-1}$ d^{-1}) – *the mean daily consumption of vegetables b.w.* (kg per $person^{-1}$) body weight (mean body weight of an adult person in these calculations – 62.8 kg [14]
- BW *(kg $person^{-1}$) – represents body weight;* 62.8 kg was adopted for calculations [14].

Non-carcinogenic risk to an adult consumer resulting from consumption of selected vegetables (carrots, cucumbers, tomatoes) was estimated based on the following formula:

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

where:
- THQ_p – *is the value of pesticides;*
- THQ_{Hm} *means the value of heavy metals;*
- ADI – obtained from the report by the NIZP-PZH [14].

HI – the measure of the potential risk of the occurrence of adverse health effects caused by the mixture of chemical compounds. This index is used in the majority of analyses for the assessment of risk for mixtures. HI for daily consumption of vegetables was calculated as follows:

$$HI = \sum_{i=1}^{n} THQ_i \qquad (3)$$

THQ has been considered as one of the main parameters of the assessment of non-cancerous risk related with the consumption of contaminated food [23]. Table 7 presents calculated THQ values for pesticides.

It is assumed that when the THQ value is less than 1, it is unlikely that the persons were exposed to the toxic level of a given contaminant in food products which, in consequence, could have a negative effect on human health [18]. Based on

Table 6. Mean daily consumption of selected vegetables according to the report by the NIZP-PZH [14]

Diet	Mean body weight [kg]	Daily consumption [g kg^{-1} b.w./day^{-1}]	Daily consumption [g $person^{-1}$ / day^{-1}]
Carrots			
Children			
DE child	16.15	1.0400	16.7960
UK infant	8.70	1.3218	11.5000
UK small child	14.60	0.5205	7.6000
DK child[1]	*21.80*	*1.3727*	*29.9249*
Adults			
PL general	62.80	0.3030	19.0254
UK adult	67.00	0.1816	13.8000
UK adult vegetarian	66.70	0.2264	15.1000
GEMS/Food G08	60.00	0.4522	27.1300
DE general	76.37	0.2630	20.0877
DE females aged 14–50	67.47	0.3055	20.613
Cucumbers			
Diet	Mean body weight [kg]	Daily consumption [g kg^{-1} b.w./day^{-1}]	Daily consumption [g $person^{-1}$ / day^{-1}]
Children			
DE child	16.15	0.6000	15.9885
UK infant	8.70	lack of data	lack of data
UK small child	14.60	0.1096	1.600
DK child	*21.80*	*1.6364*	*35.6735*
Adults			
PL general	62.80	0.0693	4.3495
UK adult	76.00	0.0605	4,6000
UK adult vegetarian	66.70	0.1064	7.1000
GEMS/Food G08	60.00	0.1838	11.0300
DE general	76.37	0.16.05	12.2550
DE females aged 14–50	67.47	0.1939	13.0836
Tomatoes			
Diet	Mean body weight [kg]	Daily consumption [g kg^{-1} b.w./day^{-1}]	Daily consumption [g $person^{-1}$ / day^{-1}]
Children			
DE child	*16.15*	*0.9900*	*15.9885*
UK infant	8.70	0.3678	3.1999
UK small child	14.60	0.5890	8.5994
Adults			
PL general	62.80	0.8830	55.4509
UK adult	76.00	0.4355	33.100
UK adult vegetarian	66.70	0.6222	41.5000
GEMS/Food G08	66.00	1.1385	68.3100
DE general	76.37	0.6577	50.2305
DE females aged 14–50	67.47	0.7394	49.8905
*GEMS/Food G06**	*60.00*	*3.5795*	*214.7700*

* FAO/WHO GEMS/Food Cluster Diet G06 2012 [22]
[1] critical diet are in italic

the calculated indices it should be stated that the THQ values are < 1, which means the lack of threat for human health related with the consumption of the analyzed vegetables if the inhabitants consumed only one type of the contaminations analyzed (active substance). The calculated values of HI for

Table 7. EDI and THQ, as well as MRL values for the residues of the selected active substances in vegetables consumed by adults (A) and children (Ch)

Vegetables	EDI		THQ		MRL
	Active substance (type of pesticide)				
	A	Ch	A	Ch	
	Boscalid				
Carrots	0.27×10^{4}	0.019×10^{4}	0.65×10^{4}	0.47×10^{3}	2.0
	Difenoconazole				
Carrots	0.15×10^{4}	0.52×10^{5}	0.15×10^{3}	0.52×10^{3}	2.0
	Tebuconazole				
Carrots	0.36×10^{5}	0.13×10^{3}	0.12×10^{3}	0.42×10^{2}	2.0
	Propamocarb				
Cucumbers	6.2×10^{6}	5.4×10^{5}	2.9×10^{5}	2.25×10^{4}	5.0
	Fluopyram				
Cucumbers	0.18×10^{2}	0.53×10^{-4}	0.0075	4.42×10^{-4}	0.5
	Fluopicolide				
Cucumbers	0.13×10^{2}	1.14×10^{-4}	0.0055	4.75×10^{-4}	0.5
	Fluopyram				
Tomatoes	0.06×10^{2}	0.75×10^{-4}	0.0052	0.63×10^{2}	0.5

consumers who consumed analyzed vegetables together with the residues of active substances (boscalid, propamocarb, fluopyram, fluopicolide and fluopyram) is 0.058 for adults and 0.012157 for children. The calculated HI values mean that no risk of the occurrence of adverse effects for consumers' health should be expected in relation to the consumption of the assessed vegetables.

Based on the presented analysis and the results included in the report by the NIZP-PZH [14], it should be stated that chronic exposure of the body to the residues of boscalid taken with carrots does not create risk for any group of consumers. The estimated exposure to the residues of boscalid in the assessed carrots, expressed as the percentage of the acceptable daily intake (ADI) calculated for the mean concentration and P95 level in the critical population is: 0.03 and 0.11% ADI, respectively. Concerning the consumption of cucumbers contaminated with active substances: propamocarb, fluopicolide, fluopyram, no risk was observed for any group of consumers. The estimated threat in any case did not exceed the specified ADI value. The highest exposure to fluopyram was found in cucumbers, resulting from the calculation of the mean concentration and P95 value. For the critical population, these values were 0.36% and 1.32% ADI, respectively. Based on the calculations performed it was found that chronic exposure to the residues of fluopyram in tomatoes does not create risk for any group of consumers. The estimated exposure expressed as a percentage of ADI calculated for the mean concentration and P95 level in the critical population is 0.28% and 0.95% ADI, respectively.

Taking into account that no incompatibilities were found with appropriate for the individual examined active substances MRL values, short term risk assessment was not carried out. Based on the data by the NIZP-PZH from literature which were available during the period of study, it was confirmed that long- and short-term intake of pesticide residues related with the consumption of tomatoes does not create risk for consumers' health [14].

Accumulation of pesticides in agricultural crops, as well as their later transfer to the food chain, is a serious public health problem worldwide. Daily exposure of the body to the residues of pesticides increases health risk for humans. The mixture of many active substances originating from pesticides may enhance this risk. However, little is still known about the toxicity of these mixtures supplied in the daily human diet. Nevertheless, they may cause impulsive repercussions due to their interactions with each other and with the environment [25, 25].

According to Yang et al., the calculated RQ values indicate that the dietary risk of fluopyram in carrots grown after applying fluopyram foliary and with irrigation to the roots, was on the level RQ < 100%, therefore, acceptable for consumers. The study revealed degradation and residual distribution of fluopyram in carrots [26].

A study by El-Sheikh et al. demonstrated that the assessment of acute (% ARfD) and chronic (% ADI) risk for consumers' health caused by residues of pesticides in carrots, which exceeds the maximum residue level is after consumption 0.2 kg for acute risk, and 0.1 kg for chronic risk. For the identified pesticide in carrots in various population groups, the values of indicators were, respectively: Lufenuron ARfD on the level of 0.0150, acute exposure (%ARfD) child 8.80, adolescent 3.77, adult 2.20, ADI 0.015, long-term exposure (%ADI) child 2.76, adolescent 1.18, and adult 0.69. In turn, with regard to cucumbers, the values for the identified pesticides were, respectively: Chlorfenapyr ARfD on the level 0.0150, acute exposure (%ARfD) child 3.20, adolescent 1.37, adult 0.80, ADI 0.015, long-term exposure (%ADI) child 1.27, adolescent 0.55, adult 0.32. Chloropirifos ARfD on the level 0.0100, acute exposure (%ARfD) child 13.33, adolescent 5.71, adult 3.33, ADI 0.01, long-term exposure (%ADI) child 3.96, adolescent 1.70, adult 0.99. Chloropirifos ARfD on the level 0.0100, acute exposure (%ARfD) child 13.33, adolescent 5.71, adult 3.33, ADI 0.01, long-term exposure (%ADI) child 3.96, adolescent 1.70, adult 0.99. Tiophanate-methyl ARfD on the level 0.2000, acute exposure (%ARfD) child 0.67, adolescent 0.29, adult 0.17, ADI 0.08, long-term exposure (%ADI) child 0.71, adolescent 0.30, adult 0.18. In turn, in the case of tomatoes for the identified pesticides, respectively: Chloropirifos ARfD on the level 0.0100, acute exposure (%ARfD) child 6.93, adolescent 2.97, adult 1.73, ADI 0.01, long-term exposure (%ADI) child 3.47, adolescent 1.49, adult 0.87. Lambda-cyhalothrin ARfD on the level 0.0050, acute exposure (%ARfD) child 19.20, adolescent 8.23, adult 4.80, ADI 0.0025, long-term exposure (%ADI) child 13.78, adolescent 5.90, adult 3.44 [27].

Limitations of the health risk assessment method. The health risk assessment method used in this study is based on simplified assumptions, which may lead either to over-estimation or under-estimation of actual consumer exposure. One of the key limitations is the assumption of 100% bioavailability of pesticide residues, whereas in reality, the absorption rate depends on multiple factors, such as the chemical properties of the compounds, the food matrix, and individual physiological characteristics of the consumer. Furthermore, the potential impact of food processing (e.g., washing, peeling, cooking), which may significantly reduce pesticide levels, was not taken into account.

The analysis was conducted for the general adult population without considering sensitive subgroups, such as the elderly or individuals with high vegetable intake. Additionally, the study focused solely on chronic (long-term) risk, while acute risk – which may arise from occasional consumption of higher doses – was not evaluated. These limitations should be taken into consideration when interpreting the results, and the estimated indicators should be regarded as preliminary, subject to refinement in future, more comprehensive assessments.

CONCLUSIONS

In order to provide high quality food, all links in the food chain – beginning with primary production, through processing, storage, distribution and sale – and ending with consumption, should be covered by strict surveillance aimed at identification of factors exerting an effect on the decrease in the quality of food. Expanding knowledge concerning contamination of vegetables with pesticides is especially important, considering the potential health risk resulting from their presence. In order to minimize adverse effects, pesticide residues should be reduced, both at the stage of agricultural production and in ready-made food products.

Dietary health risk assessment indicators should not be treated as ultimate due to the gaps extant in our knowledge regarding the routes of exposure and mechanisms of the toxic effects of pesticides. Therefore, it is recommended to carry out a complex assessment of risk covering the whole of the diet. It is also necessary to implement various surveillance plans within the food chain 'from field to table' in agriculture and the agri-food industry to reduce the content of pesticide residues in food. The most effective method of protecting public health against exposure to pesticides is the reduction of their presence in food products. In order to meet these challenges, further research activities are needed, aimed at the development of quick methods of detection and monitoring of pesticide residues *in situ*, providing safety of the environment and food, as well as improvement imn the procedures for the assessment of health risk.

Based on the data included in the report by the NIZP-PZH, the estimated health risk showed the lack of threat for the health of adult consumers related with consumption of carrots, cucumbers and tomatoes containing residues of boscalid, propamocarb, fluopyram, and fluopicolide. The calculated HI value indicates that no risk of the occurrence of adverse health effects should be expected, resulting from consumption of the mixture of the analyzed chemical compounds present in these vegetables.

It should be noted, however, that assessment was based on the assumption of 100% bioavailability of the analyzed compounds from the food matrix. Although this approach may lead to an over-estimation of the actual exposure level, it is widely accepted as a conservative scenario in dietary risk assessment. It ensures that the obtained results reflect the worst-case exposure, and are consistent with the precautionary principles adopted by international food safety authorities, such as the EFSA.

It should also be noted that the assumption of 100% bioavailability of pesticides adopted in the analysis may lead to an over-estimation of actual consumer exposure, as not all chemical compounds present in food are fully absorbed in the gastrointestinal tract. This approach allows for the estimation of maximum possible exposure and is consistent with the precautionary principle adopted by international food safety authorities, such as the EFSA. The degree of absorption depends, among other factors, on the chemical properties of the pesticide, the composition of the food matrix, and individual physiological characteristics of the consumer. Nevertheless, assuming full bioavailability is a commonly accepted approach in health risk assessment and aligns with the principle of caution; it enables the estimation of potential maximum exposure and ensures a high level of public health protection. In future studies it may be advisable to consider the differences in bioavailability between individual chemical compounds and the influence of the food matrix on their absorption.

The analysis did not include the impact of food processing (e.g. washing, peeling, cooking), which may significantly reduce pesticide residues. However, the decision to analyze raw, unprocessed samples was intentional, and aimed at providing a precautionary estimation of maximum potential exposure. Future studies should investigate the effects of common culinary practices on pesticide reduction to provide more realistic intake scenarios.

Moreover, the current assessment focused on chronic exposure in the general adult population. Sensitive subgroups, such as children, elderly people, or individuals with high vegetable consumption, were not analyzed separately due to the lack of detailed and representative consumption data. These groups may differ in dietary habits, metabolism, and body weight, which could affect the risk level. Therefore, additional studies should target these subpopulations to ensure a more comprehensive protection of public health.

Lastly, the assessment did not address the potential short-term (acute) risk related to occasional high intake of contaminated vegetables. Incorporating acute reference doses (ARfD) and estimating short-term exposure would allow for a more complete evaluation of dietary risk, particularly for compounds characterized by high acute toxicity. This aspect should be considered in future analyses as a complement to the indicators of chronic risk used in the present study.

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