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Environmental Risks of the Pesticide Use in Agrocenoses and Their Management

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ABSTRACT

The article is devoted to the development of methodical approaches to the management of environmental risks due to pesticide contamination of agrocenoses. An assessment of ecological risks due to the use of pesticides was carried out at the scientific research field of the Skvirskaya research station of organic production of the IAP of the National Academy of Sciences during the growing seasons of 2019–2021. The methods of assessing the ecological risks of potential pesticide contamination of agrocenoses based on the indicators of the agroecotoxicological index (*AETI*) and the ecotoxic impact of harmful substances (*E*) were used on the natural environment. It was shown that the level of environmental risk due to the use of pesticides in the research field of the station according to the weighted average indices (*AETI*) is characterized as low – risk, and the environmental risk due to the pesticides using is minimal. According to indicators of ecotoxicity (*E*), the pesticides that were used are characterized as having a low potential ecotoxic risk of impact on agrocenoses of cultivated plants. However, the total pesticide ecotoxicological load ($\Sigma_E = 0.425$ compared to the standard $E_{DDT} = 1$) indicates the possibility of disruption of ecological connectivities in the agroecosystem. One of the elements of environmental risk management can be the assessment of the pesticide load on agroecosystems and considering of the territory ability to self-clean. In order to minimize the environmental risks of pesticide contamination of agrocenoses, measures should be taken to regulate the use of chemical plant protection agents. This can be done by banning or limiting the use of pesticides that have a high level of ecotoxicity and are persistent in the soil. This will contribute to increasing the ecological safety of agro-ecosystems and the natural environment.

Keywords: agrocenoses, pesticides, ecological risk, ecological safety, ecotoxicity, environmental risk management.

INTRODUCTION

Agroecologists pay more and more attention to the environmental safety of the agricultural sector. This is primarily due to the significant scale of environmental pollution, the consequence of which are global climate change, biodiversity decline, pollution of agricultural products with hazardous chemicals, and land degradation [Schäfer et al. 2019, Silva et al. 2019]. The aggravation of environmental problems in a global scale has led to the creation of a new model of environmental development, which will provide favorable conditions for improving of the quality and safety and reducing the environmental degradation. Such conditions can be achieved in the process of environmental risk management, including the use of methods that guarantee minimization of the risk impact on the environment.

The analysis of foreign and domestic sources of literature shows that the principle of environmental risk reduction should be included in the risk management system in the field of environmental protection. Guidelines on the choice of risk assessment methods, the concept of their application and the structure of risk management in Ukraine are presented at the legislative level in DSTU IEC/ISO 31010:2013 “Risk Management. Methods of general risk assessment” (2015).

Furdychko and Shkuratov (2016) suppose that in the process of developing methodical approaches to environmental risk management in the agricultural sector, there is a need to have regard to threats and probable risks. In their opinion, the development of new methodical approaches to the management of environmental risks ensures the minimization of their impact on agrocenoses and the improved safety of agroecosystems [Furdychko and Shkuratov 2016].

According to the data of a number of authors, it was found that the approaches to defining the concept of environmental risk and the causes of its occurrence differ. According to Suter II (2016), environmental risks are caused by the factors affecting environmental pollution. According to Marambe et al. (2021), the greatest danger of environmental risks is caused by the long-term effects of global climate change on the ecosystem. Under these conditions, the problems of the weeds and invasive alien plants spread in agroecosystems have increased due to changes in their range and population density. The research by scientists of the Institute of Agroecology and Nature Management of the National Academy of Sciences [Moklyachuk et al. 2020] shows the possibilities of environmental risks due to the influence of climate change factors on the adaptive favorability of agroecosystems. It is scientifically proven that under the conditions of climate change it is necessary to reduce environmental risks and adaptive efficiency of agro-ecosystems of agro-climatic conditions of each region.

In the work of Lishchuk et al. (2022) outlined and summarized the main factors (abiotic, biotic, anthropogenic) of the performance of environmental risks, the sources of their occurrence, and the ecological consequences for agrocenoses due to the cultivation of agricultural crops. It is shown that the main ecological risks in agrocenoses arise as a result of the influence of a number of factors under the conditions of climate change, soil degradation, technogenic soil pollution, unsatisfactory phytosanitary state of crops, etc.

The vast majority of definitions of environmental risk due to the influence of harmful substances on the natural environment boils down to the fact that risk is the probability of the realization of a potential danger that arose as a result of the influence of anthropogenic factors or contributes to the emergence of negative consequences [Nazaruk and Botha 2020, Artemchuk et al. 2018]. In particular, the authors claim that the occurrence of environmental risk is caused by anthropogenic impact on individual components of the environment as a result of human activity. Artemchuk et al. (2018) point out that it is worth determining the quantitative assessment of potential risk, which is calculated on the basis of ecological monitoring data, taking into account the anthropogenic load on the environment. According to Zinchenko (2015), environmental risk assessment should be carried out in several stages: establishing the source of the risk; studying the nature of its impact on the natural environment; determination of the degree of danger of such influence.

The dependence of the influence of the formation of ecological risks due to anthropogenic or technogenic changes of natural objects and factors has been proven [Azarov et al. 2018]. The authors consider environmental risks as causing economic damage to the environment and assert the importance of managing such risks to minimize the negative consequences of their impact.

Considerable importance is attached to environmental risks, arising from the influence of anthropogenic factors. Such risks are directly related to the use of chemical means of plant protection – pesticides, which lead to the accumulation of toxic chemical substances in the soil and, as a result, to contamination of plant and animal products, water sources, decrease in soil fertility, etc. [Kalenyk 2011].

A number of scientists [Monarch 2014, Lewis et al. 2016, Kalenyk 2011] have a common opinion about the environmental risk that occurs during adverse changes in the natural environment under the influence of social, ecological and economic human activities. Quantitative assessment of environmental risk based on a combination of three components was considered: an integral indicator of pollution of the natural environment; damages caused by violation of the requirements of environmental protection legislation; the degree of deviation from the established norms of environmental protection measures [Karintseva 2017].

One of the main principles of the state policy for the use of pesticides, defined by the Law of Ukraine "About Pesticides and Agrochemicals" (No. 86/95-BP dated 02.03.1995), recognizes the minimization of the use of pesticides through the implementation of environmentally safe methods of farming, the use of biological or other non-chemical means plant protection, etc.

The concept of environmental risk for pesticides, as defined by Sydorchuk (2022), is considered as the probability of manifestation of their ecological safety, in particular, the ecotoxicity, for the natural environment. The assessment of such a risk should be carried out using the information about its toxicity directly to non-target species of organisms and the concentration of the toxicant in environmental objects where these organisms live.

The criteria for assessing environmental risks caused by long-term soil contamination with unsuitable pesticides were formulated and scientifically substantiated, and the environmental risks of using modern pesticides in agro-technologies of growing agricultural crops were determined [Moklyachuk et al. 2012, 2014, 2015, 2017]. The use of such criteria will contribute to the assessment of the ecological state of agro-ecosystems contaminated with pesticides and minimize the probability of a negative manifestation of the threat of environmental pollution with toxic substances.

Numerous sources of scientific literature testify to the fact that environmental risks in the agricultural sector are the most significant, since they can affect the decrease in the level of productivity of plants at any stage of ontogenesis. In Ukraine, as a result of the action of harmful organisms, the environmental risks of reducing the yield of grain crops range from 20 to 50%, which leads to the need to use chemical plant protection agents [Topchiy 2013]. However, while protecting the economic component, it is necessary to take into account the ecological consequences of the introduction of intensive plant protection technologies. Most often, ignoring the regulations for the use of chemical preparations during the cultivation of crops leads to a pesticide load on agricultural land in fairly significant volumes, which inevitably leads to the pollution of the natural environment and plant products with toxic substances [Monarch 2014, Ruda and Korshun 2017].

Despite the relevance of the issue of pesticide load on agrocenoses for growing agricultural crops, both scientists and farmers do not pay enough attention to it. The analysis of publications showed that a number of issues regarding the irrational use of pesticides, which creates threats to environmental safety in the agricultural sector, still remain unresolved. It is important to assess the agro-ecotoxic effect of pesticides and the pesticide load on the agro-ecosystem. The specifics of environmental risks and the formation of their management strategy to achieve environmental safety in the agricultural sector have not been sufficiently studied.

In this regard, the purpose of the study was to assess the environmental risks in agrocenoses for growing agricultural crops and to develop methodical approaches to their management to increase the environmental safety of the natural environment. Scientifically based methodological approaches to the assessment of environmental risks due to the use of chemical plant protection agents in agrocenoses will contribute to the minimization of potential threats to the deterioration of the ecological condition of soils and ensuring sustainable land management.

MATERIALS AND METHODS

The research was conducted in the laboratory of biocontrol of agroecosystems and organic production of the Institute of Agroecology and Environmental Management of National Academy of Agrarian Sciences of Ukraine (IAEM NAAS). The evaluation of the potential environmental risk of the use of pesticides in agrocenoses was carried out using the following methods: 1) calculation of the agroecotoxicological index (*AETI*) [Bublyk 2007]; 2) calculation of the ecotoxic effect of pesticides – ecotox (*E*) on the natural environment [Melnykov 1987]. The information base of the research involved the materials on the conditions of the traditional technology of growing agricultural plants during the growing season of 2019–2021 at the research field of the Skvirskaya Research Station of Organic Production of the IAEM NAAS (SRSOP IAEM NAAS).

Table 1. Rotational table of crop rotation of the research field of the experimental station, 2019–2021

Field plot, No.	Plot area, ha	2019	2020	2021
1	2.0	Soybean	Thistle	Mustard
2	1.0	Winter wheat	Soybean	Thistle
3	1.6	Sugar beet	Winter wheat	Soybean
4	1.0	Spring barley	Sugar beet	Winter wheat
5	0.5	Sunflower	Spring barley	Sugar beet
6	0.4	Beans	Sunflower	Spring barley
7	1.6	Mustard	Beans	Sunflower
8	1.4	Thistle	Mustard	Beans

The territory of the research station is located in the Right Bank Forest Steppe of Ukraine and is characterized by a moderately warm, moderately humid climate, favorable for the growth and development of agricultural crops. The soil of the experimental plots is low-humus, coarse-grained, medium-loamy chernozem on carbonate loess.

The scheme of the experiment of SRSOP IAEM NAAS included the cultivation of crops in a scientifically based eight-field crop rotation of the research field, namely: soybean, winter wheat, sugar beet, spring barley, sunflower, beans, mustard, and thistle (Table 1). The total area of the research field is 9.0 hectares; the number of experiment replications on each plot is triple.

Calculation of the main environmental risk of the use of pesticides

To assess the result of the ecological risk of using pesticides in the agrocenosis of the scientific research field of the SRSOP IAEM NAAS, a model for determining the agroecotoxicological index (*AETI*) was used, which takes into account the load of pesticides on the agrocenosis based on the total rate of consumption of preparations and the ability of the territory to self-purify [Bublyk 2007]. Agroecotoxicological index (*AETI*) is characterized by the following indicators: 0–1 – low risk, for which the load of pesticides on agrocenoses is compared with the ability of the territory to self-clean; 1–4 – moderately dangerous; 4–8 – increased danger; 8–10 is a high-risk index, at which the danger increases for the cultivation of fauna and the preservation of hygienic standards of the quality of agricultural products [Bublyk 2007].

The *AETI* calculation model has the form of the following Equation 1:

$$\mathrm{AETI} = \frac{10\,\frac{N_s}{Q \cdot I_{zone}}\left(1 + \frac{N_s}{Q \cdot I_{zone}}\right)^3}{\left(1 + \frac{N_s}{Q \cdot I_{zone}}\right)^4 + 5000} \tag{1}$$

where: N_S – the total consumption of pesticides throughout the season, l, kg/ha;
Q – the weighted average degree of danger of the range of pesticides;
I_{zone} – a zonal index of self-cleaning ability of agrocenoses.

The weighted average degree of danger of the range of pesticides (Q) is an indicator of the properties of pesticide preparations, it was determined by Formula 2:

$$Q = \frac{\mathrm{C}d_1 \cdot m_1 + \mathrm{C}d_2 \cdot m_2 + \dots + \mathrm{C}d_n \cdot m_n}{\mathrm{M}_s} \tag{2}$$

where: C_d – the integral degree of danger of pesticide using;
m – used amount of this pesticide, kg, l;
M_S – the total seasonal pesticides consumption on the area of the experimental field, kg, l.

The total seasonal consumption of pesticides (M_S), which used in agrocenoses of agricultural crops for protection against pests and weeds, was calculated according to Formula 3:

$$\mathrm{M}s = N_1 \cdot S + N_2 \cdot S + \dots + N_n \cdot S \tag{3}$$

where: N – is the consumption rate of each applied preparations;
S – is the area of the field.

Calculation of potential environmental risk based on the indicator of the ecotoxic effect of harmful substances – ecotox (E) on agrocenosis

The potential ecological risk of pesticides in the agrocenoses of the research field of the

SRSOP IAEM NAAS was assessed according to Melnikov's method [Melnikov 1987, Petruk et al. 2019]. This technique consists in calculating the ecotoxic effect of harmful substances (agrochemicals, pesticide preparations and their metabolites) on objects of the natural environment according to Formula 4:

$$\mathrm{E} = \frac{\mathrm{P} \cdot N_a}{LD_{50}} \tag{4}$$

where: E – ecotoxicological hazard (ecotox), conventional units;
P – the half-life of a chemical substance in environmental objects (DT_{50}), weeks;
N_a – the average consumption rate of the preparation, kg/ha;
LD_{50} – is the average lethal dose of the substance when ingested orally in rats, mg/kg.

The unit of ecotox (E) is the ecotoxicological hazard of dichlorodiphenyltrichloromethylmethane (DDT) at the rate of consumption N = 1 kg/ha, persistence P = 312 weeks and LD_{50} = 300 mg/kg [Melnykov 1897]. It is worth explaining why the insecticide DDT is taken as a standard for comparing the ecotoxicity of a chemical substance. DDT is a persistent organochlorine pesticide, very stable, toxic and able to accumulate in the body of humans and animals. Its use has a devastating effect on nature at all levels of the food chain. In many countries of the world, including Ukraine, DDT is prohibited for use.

The total ecotoxic impact (Σ_E) of dangerous substances on the experimental field was calculated, taking into account the obtained ecotox indicators (E) for all applied chemicals according to Formula 5:

$$\Sigma_E = E_1 + E_2 + \cdots + E_n \tag{5}$$

And the weighted average degree of danger of the range of pesticides in the studied territory was evaluated. To process the obtained results, standard mathematical methods of data analysis and diagram construction were adopted using *Microsoft Office Excel 2000, Statgraphics Plus for Windows*.

RESULTS AND DISCUSSION

It is well known that weather and climate conditions, such as moisture availability and temperature regime, affect the development of weeds, diseases and pests. In this regard, the range of pesticides used, their application rates and the frequency of treatments were determined, taking into account the Selianynova hydrothermal wetting coefficient (HTC). This coefficient (HTC) is the most popular indicator of droughts in Ukrainian agrometeorology [Klymenko and Trembitska 2021].

The weather and climatic conditions during the growing seasons of 2019–2021 were analyzed based on the data of the SRSOP IAEM NAAS weather station. It was found that they differed in terms of agrometeorological indicators. It should be noted that the growing seasons (2019–2021) were characterized by dry conditions that were unfavorable for the growth and development of grain crops. According to the results of the analysis of HTC (Table 2), it was found that the studied vegetation period of 2019 was sufficiently moistened in May and June (HTC = 2.3–1.4). 2020–2021 was characterized by a sufficient amount of spring precipitation in April and May (HTC = 1.7–1.8). The driest summer months were July and August (HTC = 0.3–0.8) as well as September (HTC = 0.3–0.5) in all years of research.

The system of chemical protection of plants on the research field of the experimental station was adjusted taking into account the weather conditions during the growing seasons of 2019–2021, especially waterlogging or drought (Table 3).

To prevent the active development of weeds, diseases and pests, crops were treated with

Table 2. Characteristics of weather conditions according to the hydrothermal coefficient during the growing seasons (2019–2021)

Year	HTC						Average
	April	May	June	July	August	September	
2019	0.6	2.3	1.4	0.6	0.3	0.4	0,9
2020	1.7	1.8	0.9	0.8	0.5	0.4	1,0
2021	1.7	1.8	0.9	0.8	0.4	0.4	1,0

Note: HTC scale: < 0.4 – very severe drought, 0.4÷0.5 – severe drought, 0.6÷0.7 – medium drought, 0.8÷0.9 – mild drought, 1.0 ÷1.5 – sufficient moisture, > 1.5 – excessive moisture.

Table 3. System of chemical protection of plants at SRSOP IAEM NAAS, 2019–2021

Crops	Pesticide preparation	Active ingredients (a.i.s.) of pesticide preparation	Pesticide consumption rate, l, kg/ha; l/t			
			unit of measurement	2019	2020	2021
Soybean	Bazagran	Bentazon, 480 g/l	l/ha	3.0	2.5	2.5
	Fusilade Forte 150	Fluazifop-P-butyl, 150 g/l	l/ha	1.5	2.0	1.5
	Gezagard 500	Promethrin, 500 g/l	l/ha	4.0	3.0	3.5
Winter wheat	Vitavax 200	Carboxin, 200 g/l; thiram, 200 g/l	l/ha	3.0	3.0	3.0
	Granstar Gold 75	Tribenuron-methyl, 562.5 g/kg; thifensulfuron-methyl, 187.5 g/kg	kg/ha	0.025	0.015	0.025
	Akanto Plus	Picoxystrobin, 200 g/l; cyproconazole, 80 g/l	l/ha	0.75*	0.50*	0.50*
Sugar beet	Bethanal Expert	Phenmedipham, 91 g/l; desmedipham, 71 g/l; etofumezat, 112 g/l	l/ha	1.0	1.25	1.25
	Fusilade Forte 150	Fluazifop-P -butyl, 150 g/l	l/ha	1.0	1.5	1.5
Spring barley	Vitavax 200	Carboxin, 200 g/l; thiram, 200 g/l	l/ha	3.0	3.0	3.0
	Granstar Gold 75	Tribenuron-methyl, 562.5 g/kg; thifensulfuron-methyl, 187.5 g/kg	kg/ha	0.025	0.015	0.020
	Akanto Plus	Picoxystrobin, 200 g/l; cyproconazole, 80 g/l	l/ha	0.75*	1.00*	1.00
Sunflower	Gezagard 500	Promethrin, 500 g/l	l/ha	4.0	3.0	4.0
	Nurel D	Chlorpyrifos, 500 g/l; cypermethrin, 50 g/l	l/ha	1.0	1.0	1.0
Bean	Bazagran	Bentazon, 480 g/l	l/ha	3.0	2.5	2.5
	Fusilade Forte 150	Fluazifop-P -butyl, 150 g/l	l/ha	1.5	2.0	1.5
	Gezagard 500	Promethrin, 500 g/l	l/ha	4.0	3.0	3.5
Mustard thistle	Kanonir Duo	Imidacloprid, 300 g/l; lambda-cyhalothrin, 100 g/l	kg/ha	0.015	0.015	0.015
Thistle	Kanonir Duo	Imidacloprid, 300 g/l; lambda-cyhalothrin, 100 g/l	kg/ha	0.015	0.015	0.015

Note: * – double entry.

pesticides, taking into account the duration of the drug's action, the level of disease spread, the degree of weediness of crops and plants damage by pests. The rate of consumption of pesticides corresponded to the recommendations of manufacturers of plant protection products, which guarantee obtaining high yields of agricultural crops and the effectiveness of the drugs. Pesticides of different chemical effects and directions were used in the research field of the station. In particular, the following preparations were used to protect against weeds on soybean and bean crops:

- Gezagard 500 pre-emergence herbicide (promethrin, 500 g/l) by spraying the soil before the emergence of crops from annual dicotyledonous and some grass weeds;
- Bazagran contact herbicide (active ingredients (a.i.s) bentazon, 480 g/l) by post-emergence treatment of crops to control annual dicotyledonous weeds;
- Fusilade Forte 150 selective post-emergence herbicide of systemic action ((a.i.) fluazifop-P-butyl, 150 g/l) against perennial and annual grass weeds in crop crops.

The system of chemical protection of grain crops (winter wheat and spring barley) included:

- pre-sowing treatment for treating seeds with the Vitavax 200 fungicide ((a.i.s) carboxin, 200 g/l; thiram, 200 g/l);
- treatment of crops with the Granstar Gold 75 post-emergence herbicide of systemic action (tribenuron-methyl, 562.5 g/kg; thifensulfuron-methyl, 187.5 g/kg) against annual and perennial dicotyledonous weeds;
- treatment of crops with the Akanto Plus fungicide ((a.i.s) picoxystrobin, 200 g/l; cyproconazole, 80 g/l) to protect against pathogens (ascomycetes, basidiomycetes, oomycetes, deuteromycetes).

Sugar beet crops were protected from weeds with the Bethanal Expert systemic herbicide ((a.i.s) phenmedipham, 91 g/l; desmedipham, 71 g/l; etofumezat, 112 g/l) and Fusilade Forte 150 ((a.i.) fluazifop-P-butyl, 150 g/l) for consistent repeated treatment of crops against a wide range of weeds.

Sunflower crops were treated with the Gezagard 500 preemergence herbicide (promethrin, 500 g/l) to protect seedlings from annual dicotyledonous and grass weeds. The two-component insecticide Nurel D (chlorpyrifos, 500 g/l; cypermethrin, 50 g/l) provided protection of the sunflower crop against a wide range of pests of various ranks.

During the growing season of mustard and thistle, when pests appeared, the plants were sprayed with the Kanonir Duo triple action insecticide ((a.i.s) imidacloprid, 300 g/l; lambda-cyhalothrin, 100 g/l) with a long period of protective action (contact, intestinal, systemic).

Assessment of ecological risks due to the use of chemical pesticides in the agrocenoses of the scientific research field of the SRSOP IAEM NAAS according to the indicators of the agro-ecotoxicological index

The risk assessment of the use of pesticides in the agrocenoses of the scientific research field of the SRSOP IAEM NAAS was carried out using the model for determining the agro-ecotoxicological index (AETI) [Bublyk 2007]. Calculations were performed according to formulas (1)–(3) taking into account the following initial data: the average rate of pesticide consumption during the season (N_s), the zonal index of self-cleaning (I_{zone}), the area of the plot (*S*) and the integral degree of danger of pesticide use (*Cd*). The initial data of the pesticide load and the results of the calculation of the indicators of the assessment of the potential ecological risk of the use of pesticides in the agrocenoses of the scientific research field of the SRSOP IAEM NAAS are shown in Tables 4–6.

The potential environmental risk of using pesticides is directly proportional to the rate of their consumption and inversely – to the degree of dangerousness of the preparations and the tolerance of the territory. Zonal index of the self-cleaning ability of systems (I_{zone}) characterizes the tolerance of the territory to the pesticide load and the intensity of pesticide decay depending on soil and climatic conditions. In particular, under the conditions of Ukraine, the self-cleaning index varies from 0.23 to 0.78 rating points [Bublyk et al. 1999]. According to the integral classification [Bublyk et al. 1999], indices of the self-cleaning ability of the territory are classified as follows: very intensive – > 0.80; intensive – 0.80–0.61;

Table 4. Indicators of assessment of the potential ecological risk of the use of pesticides in the agrocenoses of the scientific research field of the SRSOP IAEM NAAS, 2019

Crops	Preparation	*S*, ha	C_d	N_a, l, kg/ha	N_s, kg/ha	M_s, l, kg	*Q*	*V*, kg/ha	*AETI*, CU
Soybean	Bazagran	2.0	5	3.0	8.50	17.00	4.53	3.41	0.5450
	Fusilade Forte 150		5	1.5					
	Gezagard 500		4	4.0					
Winter wheat	Vitavax 200	1.0	3	0.6	2.13	2.13	4.44	0.87	0.0110
	Granstar Gold 75		5	0.025					
	Akanto Plus		5	1.5					
Sugar beet	Bethanal Expert	1.6	3	1.0	2.00	3.20	4.00	0.91	0.0130
	Fusilade Forte 150		5	1.0					
Spring barley	Vitavax 200	1.2	3	0.6	2.13	2.55	4.44	0.87	0.0110
	Granstar Gold 75		5	0.025					
	Akanto Plus		5	1.5					
Sunflower	Gezagard 500	0.5	4	4.0	5.00	2.50	4.00	2.27	0.1560
	Nurel D		4	1.0					
Bean	Bazagran	0.4	5	3.0	8.50	3.40	4.53	3.41	0.5450
	Fusilade Forte 150		5	1.5					
	Gezagard 500		4	4.0					
Mustard	Kanonir Duo	1.5	3	0.15	0.15	0.23	3.00	0.09	0.0002
Thistle	Kanonir Duo	0.8	3	0.15	0.15	0.12	3.00	0.09	0.0002

Note: *S* – plot area, ha; N_a – rate of application of pesticide, l, kg/ha; C_d – integral degree of danger of the preparation (Bublik, 1999); N_s – total rate of pesticide consumption, kg/ha; M_c – total seasonal consumption of pesticide, kg, l; *Q* is the weighted average degree of danger of the range of pesticides; *V* – probable pollution of the landscape, kg/ha; CU – conditional units.

moderate – 0.60–0.41; weak – 0.40–0.20; very weak – < 0.20 [Bublyk et al. 1999]. In particular, the self-purification index (I_{zone}) is 0.55 for the agrocenosis under the conditions of the Right Bank Forest Steppe of Ukraine, Kyiv region [Bublyk et al. 1999, Bublyk 2007].

According to the integral classification scale, which takes into account ecotoxicological and toxicological and hygienic indicators and has 7 degrees [Bublyk et al. 1999], pesticides are divided into: very dangerous – 1st and 2nd degree, dangerous – 3rd, moderately dangerous – 4th and 5th, slightly dangerous – 6th and 7th degree. It was determined that, according to the indicator of the integral degree of danger (C_d), the Bethanal Expert, Vitavax 200 and Kanonir Duo pesticides belong to the 3rd degree of danger. The rest of the pesticides: Gezagard 500, Nurel D, Akanto Plus, Bazagran, Granstar Gold 75 and Fusilade Forte 150 – belong to moderately dangerous – 4 and 5 degrees. The calculations of the weighted average degree of danger of pesticides (*Q*) (according to formula (2)) showed that for the agrocenoses of the research field (2019–2021), this indicator was within 3.0 (application of the Kanonir Duo insecticide on mustard and thistles) up to 5.63 (application of the Bethanal Expert and Fusilade Forte 150 herbicides on sugar beet) and were mainly characterized as dangerous and moderately dangerous (Tables 4–6).

It is known that the potential danger of the introduction of pesticides into agroecosystems for living organisms increases as the index of probable contamination of the agricultural landscape (*V*) increases. When the value of this indicator is up to 4 conventional kilograms per hectare, the ecological and hygienic situation is not dangerous. According to the data in Tables 4–6, the highest indicator of probable landscape pollution (*V*) is 3.41 kg/ha for the cultivation of soybeans and beans (2019–2021), which corresponds to a low-risk ecological and hygienic situation.

The results of the calculation of the agroecotoxicological index (*AETI*) for the growing seasons of 2019–2021 (Tables 4–6) showed that the lowest indicators were obtained when using the Kanonir Duo insecticide (on mustard and thistle) – 0.0002 CU. Slightly higher indicators of *AETI*: for cereal crops of winter wheat and spring barley (0.0066–0.0110 CU) for the use of the Vitavax

Table 5. Indicators of assessment of the potential ecological risk of the use of pesticides in the agrocenoses of the scientific research field of the SRSOP IAEM NAAS, 2020

Crops	Preparation	*S*, ha	*Cd*	*Na*, l, kg/ha	*Ns*, kg/ha	*Ms*, l, kg	*Q*	*V*, kg/ha	*AETI*, CU
Thistle	Kanonir Duo	2.0	3	0.15	0.15	0.30	3.00	0.09	0.0002
Soybean	Bazagran	1.0	5	2.50	7.50	7.50	4.60	2.96	0.3520
	Fusilade Forte 150		5	2.00					
	Gezagard 500		4	3.00					
Winter wheat	Vitavax 200	1.6	3	0.60	1.62	2.58	4.26	0.69	0.0066
	Granstar Gold 75		5	0.015					
	Akanto Plus		5	1.00					
Sugar beet	Bethanal Expert	1.2	3	1.25	2.00	3.30	5.63	0.89	0.0120
	Fusilade Forte 150		5	1.50					
Spring barley	Vitavax 200	0.5	3	0.60	2.62	1.31	4.54	1.05	0.0179
	Granstar Gold 75		5	0.015					
	Akanto Plus		5	2.00					
Sunflower	Gezagard 500	0.4	4	3.00	4.00	1.60	4.00	1.82	0.0804
	Nurel D		4	1.00					
Bean	Bazagran	1.5	5	2.50	7.50	11.25	4.60	2.96	0.3520
	Fusilade Forte 150		5	2.00					
	Gezagard 500		4	3.00					
Mustard	Kanonir Duo	1.4	3	0.15	0.15	0.21	3.00	0.09	0.0002

Note: *S* – plot area, ha; N_a – rate of application of pesticide, l, kg/ha; C_d – integral degree of danger of the preparation (Bublik, 1999); N_s – total rate of pesticide consumption, kg/ha; M_c – total seasonal consumption of pesticide, kg, l; *Q* is the weighted average degree of danger of the range of pesticides; *V* – probable pollution of the landscape, kg/ha; CU – conditional units.

200 and Akanto Plus fungicides and Granstar Gold 75 herbicide; for sugar beet (0.012–0.013 CU for crop treatment with the Bethanal Expert and Fusilade Forte 150 herbicides; for sunflower (0.0804–0.1560 CU) for crop treatment with the Gezagard 500 herbicide and the Nurel D insectoacaricide. The highest indicators of the *AETI* index were established for the use of the Bazagran, Fusilade Forte 150 and Gezagard 500 pesticides on leguminous crops (soy and beans) – 0.3520–0.5450 CU. It was established that all the obtained *AETI* indicators were within the range from 0.0002 to 0.5450 CU and refer to the low level of danger (0–1), at which the load of pesticides on agrocenoses corresponds to the ability of the territory to self-clean.

The weighted average level of the ecological risk of the use of pesticides in the research field of the station (2019–2021) was determined according to the indicators of the agro-ecotoxicological index (*AETI*) (Fig. 1).

It should be noted that the potential for the survival of fauna and ensuring the quality of agricultural products is possible when AETI ≤ 1.

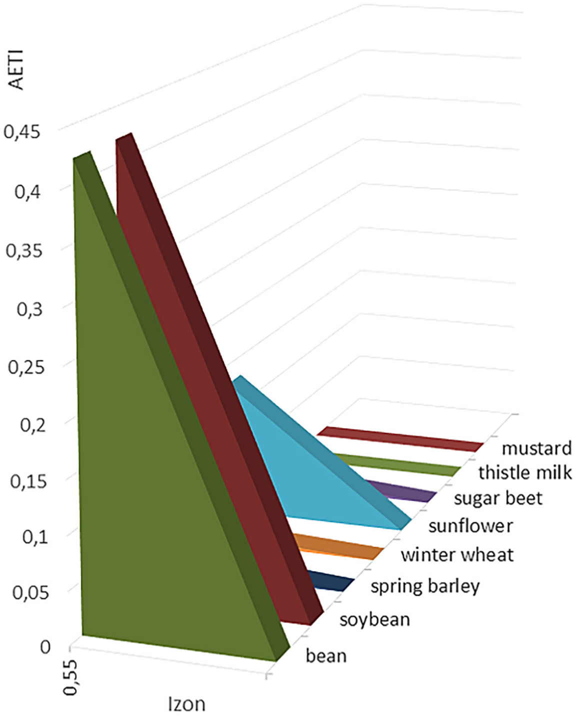

Figure 1. The level of potential danger of pesticide use in the research field of the SRSOP IAEM NAAS according to the weighted average indicators of the agro-ecotoxicological index (*AETI*) (2019–2021)

Table 6. Indicators of assessment of the potential ecological risk of the use of pesticides in the agrocenoses of the scientific research field of the SRSOP IAEM NAAS, 2021

Crops	Preparation	*S*. ha	C_d	N_a. l. kg/ha	N_s. kg/ha	M_s. l. kg	*Q*	*V*. kg/ha	*AETI*. CU
Mustard	Kanonir Duo	2.0	3	0.15	0.15	0.30	3.00	0.09	0.0002
Thistle	Kanonir Duo	1.0	3	0.15	0.15	0.15	3.00	0.09	0.0002
Soybean	Bazagran	1.6	5	2.50	7.50	12.00	4.53	3.01	0.3683
	Fusilade Forte 150		5	1.50					
	Gezagard 500		4	3.50					
Winter wheat	Vitavax 200	1.2	3	0.60	1.63	1.95	4.26	0.69	0.0067
	Granstar Gold 75		5	0.025					
	Akanto Plus		5	1.0					
Sugar beet	Bethanal Expert	0.5	3	1.25	2.00	1.34	5.63	0.89	0.0120
	Fusilade Forte 150		5	1.50					
Spring barley	Vitavax 200	0.4	3	0.60	1.62	0.65	4.26	0.69	0.0067
	Granstar Gold 75		5	0.02					
	Akanto Plus		5	1.00					
Sunflower	Gezagard 500	1.5	4	4.00	5.00	7.50	4.00	2.27	0.1558
	Nurel D		4	1.00					
Bean	Bazagran	1.4	5	2.50	7.50	10.50	4.53	3.01	0.3683
	Fusilade Forte 150		5	1.50					
	Gezagard 500		4	3.50					

Note: *S* – plot area, ha; N_a – rate of application of pesticide, l, kg/ha; C_d – integral degree of danger of the preparation (Bublik, 1999); N_s – total rate of pesticide consumption, kg/ha; M_c – total seasonal consumption of pesticide, kg, l; *Q* is the weighted average degree of danger of the range of pesticides; *V* – probable pollution of the landscape, kg/ha; CU – conditional units.

Therefore, it is necessary to plan the use of an assortment of pesticides for chemical protection of agricultural crops in such a way that AETI values are as small as possible. According to the conducted calculations, the level of the weighted average agroecotoxicological index of the use of the studied drugs (AETI) in the agrocenoses of agricultural crops was in the range from 0.0002 to 0.4217 CU. Therefore, the obtained indicators indicate a low dangerous level, and the ecological risk of using all pesticides during the three-year experiment (2019–2021) is minimal.

Assessment of ecological risks of pesticide use in agrocenoses of the scientific research field of the SRSOP IAEM NAAS according to indicators of ecotoxicological hazard (E)

Research was conducted to identify the most dangerous pesticides used in crop rotation of the scientific research field of the SRSOP IAEM NAAS, with the aim of eliminating or minimizing dangerous effects. To assess the potential environmental risk of using plant protection products in the agrocenoses of the research field, the ecotoxicological hazard (ecotox) (*E*) of pesticides was calculated according to formula (4). Calculations were made on the basis of data on: the range of pesticides, their application rates and the frequency of treatments for the above-mentioned crop rotation, toxicological and physicochemical properties of the active substances of pesticides, in particular, their persistence in the soil, toxicometric parameters, etc. The initial data and obtained calculation results are summarized in Table 7.

Using the calculated values of ecotox (*E*), the ecotoxicity of the substance under study was compared with the ecotoxicity of DDT and the relative danger of pesticide contamination of the experimental field was estimated [Melnykov 1987].

Priority indicators of the ecotoxic impact of pesticides on the environment include their toxicity, persistence in the environment, and migration ability [Moklyachuk 2014]. To determine the hazard class of a specific pesticide, one should be guided by the principles of a comprehensive assessment of its properties and taking into account the limiting criterion of harmfulness, which determines the greatest environmental risks of the use of pesticides for human health.

According to the "Hygienic classification of pesticides by degree of danger", [DSanPiN 8.8.1.2.002-98], approved by the Ministry of Health of Ukraine in 1998, pesticides are divided into four classes: I – extremely dangerous; II – dangerous; III – moderately dangerous and IV – low danger. According to oral toxicity, pesticides are divided into the following four groups: group 1 – highly toxic substances (LD_{50} < 50 mg/kg of body weight), 2 – highly toxic (LD_{50} from 50 to 200 mg/kg), 3 – moderately toxic (LD_{50} from 200 to 1000 mg/kg), 4 – low toxicity (LD_{50} > 1000 mg/kg). Therefore, according to the indicators of the semi-lethal dose of pesticides LD_{50} which are in the range from 1800 to 8000 mg/kg, the vast majority of the studied preparations according to the active substance belong to group 4 (malotoxic). These include the Akanto Plus and Vitavax 200 fungicides as well as the Bethanal Expert, Gezagard 500, Granstar Gold 75 and Fusilade Forte 150 herbicides.

Along with this, it was determined that Bazagran (LD_{50} = 500 mg/kg) belongs to group 3 – moderately toxic pesticides. It is worth noting that the highest ecotoxicity was characterized by the Kanonir Duo insecticide (a.i. imidacloprid and a.i. lambda-cyhalothrin) and Nurel D insectoacaricide (a.i. chlorpyrifos and a.i. cypermethrin). These chemicals are characterized by high toxicity according to the main indicators of acute toxicity (lethal dose LD_{50} for oral administration to the body of rats) and high indicators of persistence in the soil. In particular, the Nurel D insect acaricide according to the ecotoxicity indicators of a.i. chlorpyrifos (LD_{50} = 66 mg/kg) belongs to 2 groups – highly toxic pesticides, and a.i. cypermethrin (LD_{50} = 287 mg/kg) – up to 3 groups – moderately toxic pesticides. Instead, Kanonir Duo insecticide, which has two active substances in its composition, turned out to be the most toxic drug in terms of oral toxicity. According to a.i. imidocloprid (LD_{50} = 131 mg/kg) and a.i. lambda-cyhalothrin (LD_{50} = 56 mg/kg) Kanonir Duo belongs to group 2 – highly toxic substances.

It is generally known that the half-life of a pesticide in the soil to half its initial concentration (DT_{50}) is an indicator of its stability. According to the classification of the OSU Extension Pesticide Properties Database [NPIC], pesticides are classified into three groups: non-persistent (DT_{50} < 30 days), moderately persistent (DT_{50} – from 30 to 100 days), persistent – (DT_{50} > 100 days). In Ukraine, the assessment of the stability of pesticides in the soil is carried out in accordance with the current regulatory documents, namely DSanPiN 8.8.1.002-98. According to this hygienic classification, according to the stability in the soil, pesticides are divided into the following four classes: I – highly resistant ($DT_{50} > 60$ days), II – resistant (DT_{50} – from 31 to 60 days), III – moderately resistant (DT_{50} – from 11 to 30 days), IV – slightly stable ($DT_{50} < 11$ days).

Therefore, active substances cyproconazole (142 days), imidacloprid (191 days), lambda-cyhalothrin (65 days), chlorpyrifos (76 days), and cypermethrin (69 days) have the highest stability in the soil. According to DSanPiN 8.8.1.002-98, these chemical substances can be attributed to the I class of danger – highly resistant pesticides. Class II (persistent) includes the following active substances of pesticides: picoxystrobin (24 days), bentazone (45 days), phenmedipham (37 days) and promethrin (41 days). Moderately persistent class III pesticides – thiram (15 days), desmedifam (17 days) and tribenuron-methyl (14 days). Class IV – low-resistant pesticides include carboxin (3.3 days), etofumesate (7 days), thifensulfuron-methyl (10 days) and fluazifop-P-butyl (8.2 days).

It should be noted that indicators of the half-life of pesticides in the soil are usually approximate and may differ, since the stability of the chemical substance depends on the soil and climatic conditions of the research area (mechanical composition of the soil, pH, humus content, temperature and humidity of the soil). In addition, the persistence of pesticides in the soil depends on their ability to cause microbiological destruction, photolytic degradation, adsorption by soil colloids, etc.

According to the results of the evaluation of the ecotoxicological risk of the use of pesticides,

Table 7. Ecotoxicological hazard of pesticide load on the agrocenosis of the research field of the SRSOP IAEM NAAS, 2019–2021

The name of the pesticide	Active ingredients (a.i.s), g/l, kg	The crop on which the pesticide is applied	N_a, l, kg/ha *	LD_{50}, mg/kg **	DT_{50}, (P), days/weeks ***	$E_{a.i.s.}$, CU****	E, CU******
Fungicides							
Akanto Plus	Picoxystrobin, 200	Winter wheat, spring barley	1.33	> 5 000	24.0/3.42	$9.09 \cdot 10^{-4}$	$7.80 \cdot 10^{-2}$
	Cyproconazole, 80			< 350	142.0/20.29	$7.71 \cdot 10^{-2}$	
Vitavax 200	Carboxin, 200	Winter wheat, spring barley	0.6	2588	3.3/0.47	$1.09 \cdot 10^{-4}$	$8.22 \cdot 10^{-4}$
	Thiram, 200			> 1800	15.0/2.14	$7.13 \cdot 10^{-4}$	
Herbicides							
Bazagran	Bentazon, 480	Soybean. Bean	2.67	500	45.0/6.43	$3.43 \cdot 10^{-2}$	$3.43 \cdot 10^{-2}$
Bethanal Expert	Phenmedipham, 91	Sugar beet	1.17	> 8000	37.0/5.28	$7.72 \cdot 10^{-4}$	$4.58 \cdot 10^{-3}$
	Desmedipham,71			> 5000	17.0/2.43	$5.69 \cdot 10^{-4}$	
	Etofumezat, 112			> 5000	7.0/13.86	$3.24 \cdot 10^{-3}$	
Gezagard 500	Prometryn, 500	Soybean. Bean, sunflower	3.56	> 2000	41.0/5.86	$1.04 \cdot 10^{-2}$	$1.04 \cdot 10^{-2}$
Granstar Gold 75	Tribenuron-methyl, 562,5	Winter wheat, spring barley	0.021	> 5000	14.0/2.00	$8.40 \cdot 10^{-6}$	$1.44 \cdot 10^{-5}$
	Thifensulfuron-methyl, 187,5			> 5000	10.0/1.43	$6.00 \cdot 10^{-6}$	
Fusilade Forte 150	Fluazifop-P-butyl, 150	Soybean, bean	1.67	2451	8.2/1.17	$7.98 \cdot 10^{-4}$	$7.98 \cdot 10^{-4}$
Insecticides							
Kanonir Duo	Imidacloprid, 300	Mustard, thistle	0.15	131	191.0/27.28	$3.12 \cdot 10^{-2}$	$1.01 \cdot 10^{-1}$
	Lambda-cyhalothrin, 100			20	65.0/9.28	$6.96 \cdot 10^{-2}$	
Insectoacaricides							
Nurel D	Chlorpyrifos, 500	Sunflower	1.0	66	76.0/10.85	$1.61 \cdot 10^{-1}$	1.95^{-1}
	Cypermethrin, 50			287	69.0/9.86	$3.44 \cdot 10^{-2}$	
The total ecotoxicological load, $\sum_E$						$4.25 \cdot 10^{-1}$	

Note: *N – average rate of pesticide consumption, l, kg/ha; **LD_{50} – ecotoxicity of a chemical substance, mg/kg; ***DT_{50} (P) – half-life of a chemical substance, days/weeks; ****$E_{a.i.s.}$ – environmental hazard of the active substance of the pesticide, as specified; ******E – ecological hazard of pesticide preparation, CU.; CU – conditional units the indicators of ecological hazard (E) according to the active substance of fungicides ranged from $E_{a.i.\ carboxin} = 1.09 \cdot 10^{-4}$ CU (Vitavaks 200) to $E_{a.i.\ cyproconazole} = 7.71 \cdot 10^{-2}$ CU (Acanto Plus). For herbicides, ecotox indicators ($E_{a.i.}$) were slightly lower and were determined within the limits of $E_{a.i\ thifensulfuron\text{-}methyl} = 6.0 \cdot 10^{-6}$ CU (Granstar Gold 75) to $E_{a.i.\ bentazone} = 3.43 \cdot 10^{-2}$ CU (Bazagran). The highest ecotoxicity was characterized by the active substances of the Kanonir Duo insecticide ($E_{a.i\ imidacloprid} = 3.12 \cdot 10^{-2}$ CU; $E_{a.i\ lambda\text{-}cyhalothrin} = 6.96 \cdot 10^{-2}$ CU) and the Nurel D insectoacaricide ($E_{a.i\ chlorpyrifos} = 1.61 \cdot 10^{-1}$ CU; $E_{a.i\ cypermethrin} = 3.44 \cdot 10^{-1}$ CU).

Thus, it was established that the ecological risk of using pesticides in all areas of the station's research crop rotation is lower by 1–5 orders of magnitude compared to DDT. In general, the ecotoxicological hazard of the Granstar Gold 75 herbicide was five orders of magnitude lower compared to DDT ($E_{GranstarGold\ 75} = 1.44 \cdot 10^{-5}$ CU), which allows characterizing the studied preparation as a low-toxic pesticide (I degree), which has a low potential ecotoxic risk of impact on agrocenoses of winter wheat and spring barley.

Ecotoxicity of the Vitavax 200 fungicide ($E_{Vitavax\ 200} = 8.22 \cdot 10^{-4}$ CU), used for treating winter wheat and spring barley seeds, and the Fusilade Forte 150 herbicide ($E_{Fusilade\ Forte\ 150} = 7.98 \cdot 10^{-4}$ CU) for the protection of agrocenoses from weeds of soybean and bean crops, were four orders of magnitude lower compared to DDT.

The Bethanal Expert herbicide, used to protect sugar beet crops from weeds, was characterized by ecotoxicity indicators three orders of magnitude lower compared to DDT ($E_{Bethanal\ Expert} = 4.58 \cdot 10^{-3}$ CU).

Ecotoxicity indicators (E) were two orders of magnitude lower compared to the standard DDT for: Acanto Plus fungicide ($E_{Acanto\ Plus} = 7.80 \cdot 10^{-2}$ CU), which was used to treat crops of cereal crops to protect against pathogens; Gezagard 500 pre-emergence herbicide ($E_{Gezagard\ 500} = 1.04 \cdot 10^{-2}$ CU) and Bazagran post-emergence contact herbicide ($E_{Bazagran} = 3.43 \cdot 10^{-2}$ CU), which were used to control annual dicotyledonous and some cereal weeds in soybean, bean and sunflower crops.

The highest ecotoxicity of pesticides (E), which was determined by the sum of the ecotoxes of the corresponding active substances of pesticides ($E_{a.i}$), was established for the Kanonir Duo insecticide ($E_{Kanonir\ Duo} = 1.01 \cdot 10^{-1}$ CU) and the Nurel D insectoacaricide ($E_{Nurel\ D} = 1.95 \cdot 10^{-1}$ CU), which provided protection of sunflower, mustard and thistle crops from a wide range of pests. The obtained indicators were only one order of magnitude lower compared to DDT.

The analysis of the obtained values of ecotox (E) and ($E_{a.i}$) allows to characterize the investigated pesticides as having a low potential ecotoxic risk of impact on agrocenoses of cultivated plants.

However, it is worth noting that even minimal exposure to chemicals carries an ecotoxicological burden on the natural environment, which disrupts ecological relationships due to the destruction of insects, fungi, bacteria, aquatic organisms, plants, etc. In this regard, despite the lower values of ecotox (E) compared to the DDT standard, it can be stated that the use of chemical plant protection agents can create a potential ecological risk of contamination of agrocenoses of agricultural crops.

For practical application and to reduce the ecological risk of pesticide load on the experimental field, it is possible to replace pesticide preparations with high ecotoxicity indicators (E) with safer ones that have a shorter half-life (DT_{50}) and/or a lower ecotoxicity effect on living organisms (LD_{50}).

The total ecotoxicological load (Σ_E) was analyzed, which was calculated according to formula (5) taking into account the ecotox indicators (E) for all chemical pesticides that were used in the crop rotation of the experimental field of the SRSOP IAEM NAAS. It was established that the weighted average value of pesticide load on the studied territory ($\Sigma_E = 0.425$ CU) during the growing seasons of 2019–2021 is quite significant (compared to $E_{DDT} = 1$), which indicates a possible potential ecological risk for agrocenoses of agricultural plants.

The final stage of environmental risk assessment is the adoption of regulatory decisions regarding their management. Since the long-term repeated use of pesticides clearly leads to the accumulation of their residues or metabolites in the soil and, as a result, is a source of contamination of plant products and environmental objects; therefore, the use of the results of the assessment of the pesticide load on agroecosystems, taking into account the ability of the territory to self-clean, can be considered as one of environmental risk management instruments. In particular, in order to minimize environmental risks for the agroecosystem and prevent pollution of the natural environment, it is necessary to take measures to regulate the use of pesticides, such as limiting or banning their use, reducing the application rate, selecting the least toxic, and replacing chemical means of plants with biological ones.

CONCLUSIONS

It was determined that the level of ecological risk of the use of pesticides in the crop rotation of the scientific research field of the Skvirskaya research station of organic production of the IAEM of the National Academy of Sciences (vegetation 2019–2021) according to the average weighted indicators of the agro-ecotoxicological index (*AETI*) is characterized as slightly dangerous and is in the range from 0.002 to 0.4217 CU, and the ecological risk of using pesticides is minimal.

The potential ecological risk of pesticide use can be assessed by indicators of the properties of pesticide preparations, such as the ecotoxicity of a chemical substance, its quantitative load on the cultivated area, persistence in the soil and the tolerance of the area in certain soil and climatic conditions. According to the ecotoxicity indicators (E), the studied pesticides are characterized as having a low potential ecotoxic risk of impact on agrocenoses of cultivated plants. However, the total pesticide ecotoxicological load (Σ_E) on the agrocenosis of the research field ($\Sigma_E = 0.425$ per unit compared to the standard $E_{DDT} = 1$) indicates a significant potential ecological risk for the agrocenosis and the possibility of disruption of ecological relationships in the agroecosystem due to destruction of insects, fungi, bacteria, aquatic organisms, etc. The obtained indicators of the total pesticide ecotoxicological load (Σ_E) are the evidence that the use of the researched chemical plant protection agents can create a potential ecological risk of pesticide contamination of agrocenoses of agricultural crops.

Using the results of the assessment of the pesticide load on agroecosystems, taking into account the ability of the territory to self-clean, can be considered as one of the instruments of environmental risk management. In particular, from the point of view of environmental risk management for agrocenoses, measures should be taken to regulate the use of chemical plant protection agents by prohibiting or limiting the use of certain pesticides that have a high level of ecotoxicity and a long period of persistence in the soil, reducing the rate of introduction, selection and use of the least toxic to prevent as well as minimize environmental risks of pollution of the agroecosystem and natural environment, etc.

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