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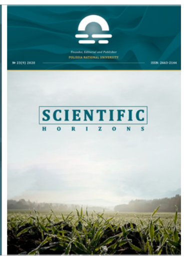

Accumulation of cadmium and lead in the organs and tissues of dairy cows depending on breed and diet

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Abstract. Agroecosystem monitoring in a time of full-scale war has shown a high level of anthropogenic impact and an increase in the contamination of the environment with heavy metals, including toxic Cd and Pb. This study aimed to analyse the content of cadmium and lead in the kidneys, liver, lungs, heart, spleen, bone and muscle tissues of dairy cows depending on breed and diet under the conditions of environmentally safe cow's milk production technology. Experiments were conducted on dairy cows of different breeds in farms located within the Forest-Steppe soil and climatic zone of Ukraine, with control slaughter performed at the end of the experiment. The highest Cd content was found in the kidneys of cows of the Ukrainian Black-and-White Dairy breed on a silage-hay diet with the values 2.968 ± 0.193 mg/kg and on a silage-root crop diet with the values 3.241 ± 0.318 mg/kg, and the highest Pb content was found on the silage-hay diet with the values 4.387 ± 0.092 mg/kg and silage-root crop diet with the values ± 0.546 mg/kg. Analysis of muscle tissue for Cd content showed the highest concentration in Ukrainian Black-and-White Dairy cows fed a silage-hay diet, amounting to 0.125 ± 0.026 mg/kg, and a silage-root crop diet, amounting to 0.140 ± 0.006 mg/kg. The Pb concentration in muscle tissue was also highest in Ukrainian Black-and-White Dairy cows, reaching 1.472 ± 0.065 mg/kg under the silage-hay diet and 1.691 ± 0.092 mg/kg under the silage-root crop diet. The highest concentrations of Cd and Pb in the kidneys, liver, lungs, spleen, heart, bones and muscle tissue were identified in Ukrainian Black and-White Dairy cows compared with animals of the Ukrainian Red-and-White Dairy breed, which was associated more with the higher intake of pollutants from the basal diets and feeding type than with breed characteristics. The obtained data may be used in the development of recommendations for selecting diet types and feeding technologies for dairy cows in order to reduce the accumulation of heavy metals in internal organs and tissues, as well as to improve the environmental safety of cows' milk and dairy products

Keywords: ecotoxicants; feed; feeding type; heavy metals; productive animals; agroecosystems

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INTRODUCTION

The production of environmentally safe livestock products under conditions of technogenic environmental contamination is one of the key challenges facing the modern agricultural sector. High anthropogenic loads of ecotoxicants on agrobiogeocenoses cause changes in the natural state of soils, water bodies, flora, fauna and microorganisms. Similar processes are also characteristic of territories affected by military activity, where the use of ammunition and military equipment results in additional metal input into the environment, according to A.J. Barker *et al*. (2021). Heavy metals, especially the elements of cadmium and lead, have a particularly dangerous characteristic due to their highly bioaccumulative features and tendency to accumulate in the body of livestock, thereby affecting their physiological status and the safety of products from farm animals. Cattle, in this case, are of great importance as a source of milk and meat, as well as indicators of the environmental situation of agricultural land. In addition, the pollution of livestock with heavy metals is aggravated by the consequences of russia's military aggression against Ukraine, which has been ongoing since 2022, due to the release of various toxic compounds, including cadmium, lead, mercury, copper, and zinc, during the explosion of landmines and explosives on agricultural land. It has been proven by M. Solokha *et al*. (2023) that military actions, through field and remote sensing observation, lead to significant changes in the physicochemical parameters of soils and accumulation of toxic elements in the environment, which leads to their penetration into the feed base and further to their accumulation in the organisms of animals. Therefore, researching the regularities of cadmium and lead accumulation in the organs and tissues of productive dairy cows is particularly relevant for assessing the environmental safety of livestock products and selecting appropriate mitigation strategies.

The accumulation of heavy metals, in particular cadmium and lead, in the soil results in their transfer into plant products, resulting in the risk of contamination of the food chain and harmful effects on human health. According to V.O. Velychko (2023) and S. Portiannyk *et al*. (2024), under conditions of increased anthropogenic pressure on the environment and farm animals, monitoring of heavy metals within the "soil – plant (feed) – animal products (milk, meat, etc.) – human" system remains a priority area of scientific research. Cadmium and lead entering the bodies of cows through feed are readily absorbed in the gastrointestinal tract into the bloodstream, distributed throughout the organism and excreted with milk and faeces; however, part of these metals accumulates in internal organs and tissues, where they may persist for long periods. An important area of research for Ukrainian scientists is the assessment of the effects of different diet types and the sorbent saponite, various protein-vitamin-mineral supplements in feed mixtures, mineralvitamin premixes and biologically active preparations on the level of cadmium accumulation in the muscle tissue of bulls, pigs and dairy cows. I.M. Savchuk *et al*. (2021, 2023) substantiated the feasibility of using silage-concentrate, silage-concentrate-root crop and silageconcentrate-haylage diet types for fattening young cattle and determined their effects on cadmium and lead accumulation in animal products. The use of silage-concentrate-root crop and silage-concentrate-haylage diets in bull feeding reduced cadmium accumulation in muscle tissue by 34.1%-66.7% and its concentration in the liv er by 15.3%-46.6% compared with silage-concentrate diets.

Researchers from Malaysia, Z.F. Anual *et al*. (2023), collected 378 samples of edible animal by-products from markets to determine heavy metal content. The highest lead concentration was detected in cattle lungs (0.11 ± 0.20 mg/kg), as well as in the spleen (0.09 ± 0.14 mg/kg) and rumen (0.09 ± 0.12 mg/kg). With regard to cadmium, the highest concentrations were identified in cattle liver (0.13 ± 0.12 mg/kg), pig liver (0.08 ± 0.05 mg/kg) and chicken liver (0.03 ± 0.02 mg/kg). M.H. Emami *et al*. (2023) determined the content of lead and cadmium in muscles, lungs, heart, liver, spleen and other organs and tissues. The study showed that the accumulation of the heavy metals cadmium and lead in cattle tissues was lower than in goats or lambs, which was attributed to differences in animal size, feeding regimes and housing conditions. The muscle tissue of cows kept outdoors accumulated more lead than that of cows housed indoors.

R.A. Samy *et al*. (2025) examined 150 samples of buffalo muscle, liver and kidney tissues in order to determine heavy metal content and assess risks to consumer health. Cadmium and lead were found in all tissues at varying concentrations, with the highest levels being in the liver and kidneys and the lowest in muscle. A. Mushtaq *et al*. (2024), having analysed 180 samples of cattle muscle tissue, liver and kidneys obtained from slaughterhouses in Pakistan for six heavy metals, found that the liver, compared with muscle tissue and kidneys, was the primary organ for the bioaccumulation of chromium, lead and mercury. Investigating the problem of heavy metal nephrotoxicity in cattle and its treatment, I. Tahir & K.A. Alkheraije (2023) concluded that lead and cadmium exhibit high nephrotoxicity, while these pollutants cause acute kidney diseases in cattle, accumulate in other parts of the body and penetrate the liver and muscles, although with lower intensity compared with the kidneys.

At the same time, despite the considerable number of studies conducted in different countries worldwide, the issue of heavy metal accumulation in livestock products under Ukrainian conditions, particularly with regard to the specific features of anthropogenic pressure and the consequences of military activities, remains insufficiently investigated. Of particular relevance is the study of the influence of breed and feeding type on the level of cadmium and lead accumulation in the tissues of lactating cows. This study aimed to analyse the accumulation of the toxic heavy metals cadmium and lead in the internal organs and tissues of lactating cows depending on breed and feeding type under conditions of applying new technological approaches to the production of environmentally safe cow's milk on cattle farms.

MATERIALS AND METHODS

The study was conducted in four farms located in the Lubny District of Poltava Region within the Forest-Steppe zone of Ukraine. The study involved 420 dairy cows of the Ukrainian BlackandWhite Dairy and Ukrainian Red-and-White Dairy breeds. All animal manipulations were performed in accordance with the Law of Ukraine No. 249 (2012) and the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (1986). The laboratory complied with the requirements of ISO/IEC 17025:2005 (2006) concerning the general requirements for the competence of testing and calibration laboratories.

The agricultural lands where the animals were kept and where feed components for the basal diets were cultivated were located near environmentally hazardous anthropogenic facilities and differed in the level of technogenic pressure, including the Kyiv-Kharkiv-Dovzhanskyi highway, oil pipelines, gas pipelines and gas compressor stations. The cows were fed four types of diets: silage-root crop, silage-hay, silage-haylage and silage-haylage-concentrate. The distribution of cows according to feeding type and location is presented in Table 1.

***Table 1**. Classification of the feeding types according to location*

Feeding type	Industrial facility	Distance from the facility, km	Number of animals, head
Silage-root crop	Automobile gas-filling compressor station	3	130
Silage-hay	Gas condensate station	10	800
Silage-haylage	Industrial centre	18	250
Silage-haylage-concentrate	Kyiv-Kharkiv-Dovzhanskyi highway	30	500

***Source:** developed by the author*

The study was carried out in the autumn–spring periods of cow keeping (2017-2018) in two stages, namely comparative (42 days) and experimental (120 days). The cows were divided into three groups: control group I (n = 12) and experimental groups II and III (n = 12 and n = 12, respectively). The animals were selected by the analogue method according to live weight and productivity, and were in the third lactation period, which corresponds to peak milk productivity. The average live weight of the cows at the time of the study ranged from 500 to 545 kg. The average daily milk yield was 14.0-14.8 kg. The breed composition of cows, depending on the type of feeding, is given in Table 2.

The animals of all experimental groups were fed by the developed basic diet balanced on feed units, digestible protein and other nutrients, although in all samples of feeding materials there was an excess of the concentrations of cadmium, lead, copper and zinc above the maximum permissible level. The composition of each feeding type is presented in Table 3.

***Table 2**. Breed composition of cows depending on the type of feeding*

Breed	Feeding type	Number of animals in each group, head			
		I	II	III	Total
BlackandWhite	Silage-root crop	12	12	12	36
	Silage-hay	65	65	65	195
Red-and-White	Silage-haylage	21	21	21	63
	Silage-haylage-concentrate	42	42	42	126

***Source:** developed by the author*

***Table 3**. Diet composition and cadmium and lead content depending on feeding type*

Feeding type	Designation	Composition	Heavy metal content, mg/kg	
			Cd	Pb
Silage-root crop	BD1	grass-legume hay	0.96	28.59
		wheat straw	0.71	13.62
		maize silage	0.69	13.51
		lucerne haylage	0.75	16.78

Table 3. Continued

Feeding type	Designation	Composition	Heavy metal content, mg/kg	
			Cd	Pb
Silage-root crop	BD1	fodder beet	0.64	12.22
		ground maize grain	0.96	20.51
Silage-hay	BD2	lucerne hay	0.57	11.22
		wheat straw	0.51	12.5
		maize silage	0.39	9.13
		lucerne haylage	0.45	9.54
		fodder beet	0.75	17.21
		ground barley grain	0.54	11.6
Silage-haylage	BD2	lucerne hay	0.63	16.51
		grass-legume hay	0.66	18.5
		maize silage	0.48	12.5
		lucerne haylage	0.54	15.5
		ground oat grain	0.75	23.12
		ground pea grain	0.78	23.51
Silagehaylageconcentrate	BD2	lucerne hay	0.69	16.52
		grass-legume hay	0.75	36.51
		maize silage	0.42	10.54
		lucerne haylage	0.48	14.23
		ground maize grain	0.54	18.51
		ground pea grain	0.63	20.53

Note: *maximum permissible concentrations in feed: Cd – 0.3 mg/kg; Pb – 5.0 mg/kg*
Source: *developed by the author*

In the second experimental group, the basal diet was supplemented with the mineral-vitamin premix "MP-A" to correct macro- and microelement nutrition and reduce the toxic heavy metal burden on the organism. The premix contained mineral elements including iron, manganese, cobalt, selenium, sulphur, magnesium, calcium, phosphorus and iodine, as well as the amino acid methionine and vitamins A, D, E, B2, B3, B4, B6, C and H. In the third experimental group, in addition to feeding the basal diet supplemented with the premix, intramuscular injections of the phytobiological preparation "BP-9", based on extracts of medicinal plants, were administered. The preparation contained five-flavour fruit (*Schizandra chinensis* (Turcz.) Baill.), chamomile (*Chamomilla recutita*), Siberian ginseng (*Eleutherococcus senticosus* (*Acanthopanax senticosus*)), common sage (*Salvia officinalis*), common barberry (*Berberis vulgaris*), lucerne (*Medicago sativa*), Java tea (*Orthosiphon stamineus*), sea buckthorn (*Hippophae rhamnoides*) and common vervain (*Verbena officinalis*). The role of the biological preparation was to enhance the antidotal effect of the premix and influence target organ cells in order to intensify the elimination of ecotoxicants from the organism. The feeding scheme for each group of cows is presented in Table 4.

Table 4*. Scheme of experimental groups in each experiment*

Feeding type	Group		
	I	II	III
Silage-root crop	BD1	BD1 + premix "MP-A1"	BD1 + premix "MP-A1" + preparation "BP-9"
Silage-hay	BD2	BD2 + premix "MP-A2"	BD2 + premix "MP-A2" + preparation "BP-9"
Silage-haylage	BD3	BD3 + premix "MP-A3"	BD3 + premix "MP-A3" + preparation "BP-9"
Silagehaylageconcentrate	BD4	BD4 + premix "MP-A4"	BD4 + premix "MP-A4" + preparation "BP-9"

Note: *BD – basal diet; BP – biologically active preparation; MP – mineral premix*
Source: *developed by the author*

At the last stage of the study, an acute experiment was conducted, involving the slaughter of animals from each group (n = 3) and collecting samples of biologically relevant tissue in the internal organs to conduct veterinary and sanitary analysis of it. Sampling of muscle tissue, internal organs (kidneys, liver, lungs, heart and spleen), and bone tissue was carried out on the basis of the methodical recommendations of E.I. Chygrinov *et al*. (1998) and O.M. Yakubchak *et al*. (2005). Representative samples were prepared by collecting three-point samples weighing 100 g each from different parts of every organ, followed by their combination and homogenisation to obtain an integrated sample weighing 250-300 g. The collected samples were placed in sterile sealed containers, stored at a temperature of +2°C to +8°C and transported to the laboratory together with the accompanying documentation (sampling report). Statistical analysis was performed on the basis of the calculated mean value of the parameter in the sample (M) with standard deviation (SD). The results are presented as M ± SD. Differences between mean values were considered statistically significant at $p < 0.05$. The level of significance was assessed using one-way ANOVA. Calculations were performed using STATISTICA software version 10.0.

RESULTS AND DISCUSSION

During the examination of the internal organs after control slaughter, no pathological changes or abnormalities in shape or colour were detected. Table 5 presents the content of the ecotoxicants cadmium and lead in the internal organs and tissues of animals from control group I, depending on breed type.

***Table 5**. Cadmium and lead content in the organisms of cows from group I (mg/kg fresh weight)*

Organ	Breed							
	Black-and-White				Red-and-White			
Kidneys	Cd	2.968-3.241	Pb	4.387-4.522	Cd	2.305-2.634	Pb	3.452-3.981
Liver		0.701-0.752		1.731-1.865		0.611-0.683		1.607-1.694
Lungs		0.451-0.513		2.465-2.763		0.331-0.393		1.812-2.228
Spleen		0.462-0.486		1.480-1.503		0.361-0.391		1.029-1.279
Heart		0.431-0.459		1.091-1.146		0.337-0.395		0.840-0.957
Bones		0.411-0.423		1.512-1.685		0.392-0.407		1.234-1.480
Muscles		0.125-0.140		1.472-1.691		0.094-0.115		1.083-1.264

***Source:** developed by the author*

The data presented in the table demonstrate that the principal target organs for cadmium and lead accumulation in both breeds were the kidneys and liver. Accumulation of heavy metals was also recorded in the lungs, spleen, heart, as well as in bone and muscle tissues. The highest Cd concentration was identified in the kidneys of Black-and-White cows fed silage-hay diets, amounting to 2.968 ± 0.193 mg/kg, and silage-root crop diets, amounting to 3.241 ± 0.318 mg/kg, compared with Red-and-White cows, in which the pollutant concentration was recorded at 2.305 ± 0.033 mg/kg in animals receiving the silage-haylage-concentrate diet and 2.634 ± 0.093 mg/kg in those fed the silage-haylage diet.

Table 6 presents descriptive statistics of cadmium content in the kidneys. A similar pattern was observed for the other dangerous ecotoxicant – Pb. The maximal concentration of this ecotoxicant in kidneys was detected in Ukrainian Black-and-White Dairy cows fed silage-hay (4.387 ± 0.092 mg/kg) and silage-root crop (4.522 ± 0.546 mg/kg) diets, while it was lower in Ukrainian Red-and-White Dairy cows, which were fed silage-haylage-concentrate diet (3.452 ± 0.017 mg/kg) or silage-haylage diet (3.981 ± 0.274 mg/kg).

***Table 6**. Statistics of cadmium concentration in the kidneys of cows from group I, mg/kg*

Breed	Feeding type	Mean	Median	Minimum	Maximum	Lower Quartile	Upper Quartile	Std. Dev	Standard Error
BlackandWhite	Silage-root crop	3.241	3.322	2.891	3.511	2.891	3.511	0.318	0.183
	Silage-hay	2.968	2.858	2.855	3.191	2.855	3.191	0.193	0.112
Red-and-White	Silage-haylage	2.634	2.619	2.549	2.734	2.549	2.734	0.093	0.054
	Silagehaylageconcentrate	2.305	2.318	2.268	2.329	2.268	2.329	0.033	0.019

***Source:** developed by the author*

According to the quartile diagram presented in Figure 1, the degree of variation can be assessed. The graph reflects the dispersion of lower and upper values, while the median does not differ substantially from the arithmetic mean. Among the maximal concentration values, the highest one was noted in the kidneys of the animals fed a silage-root crop diet (3.511 mg/kg), while the lowest one occurred under a silage-haylage-concentrate diet (2.329 mg/kg). The minimum of cadmium values, 2.268 mg/kg, was identified among animals receiving a silagehaylageconcentrate diet.

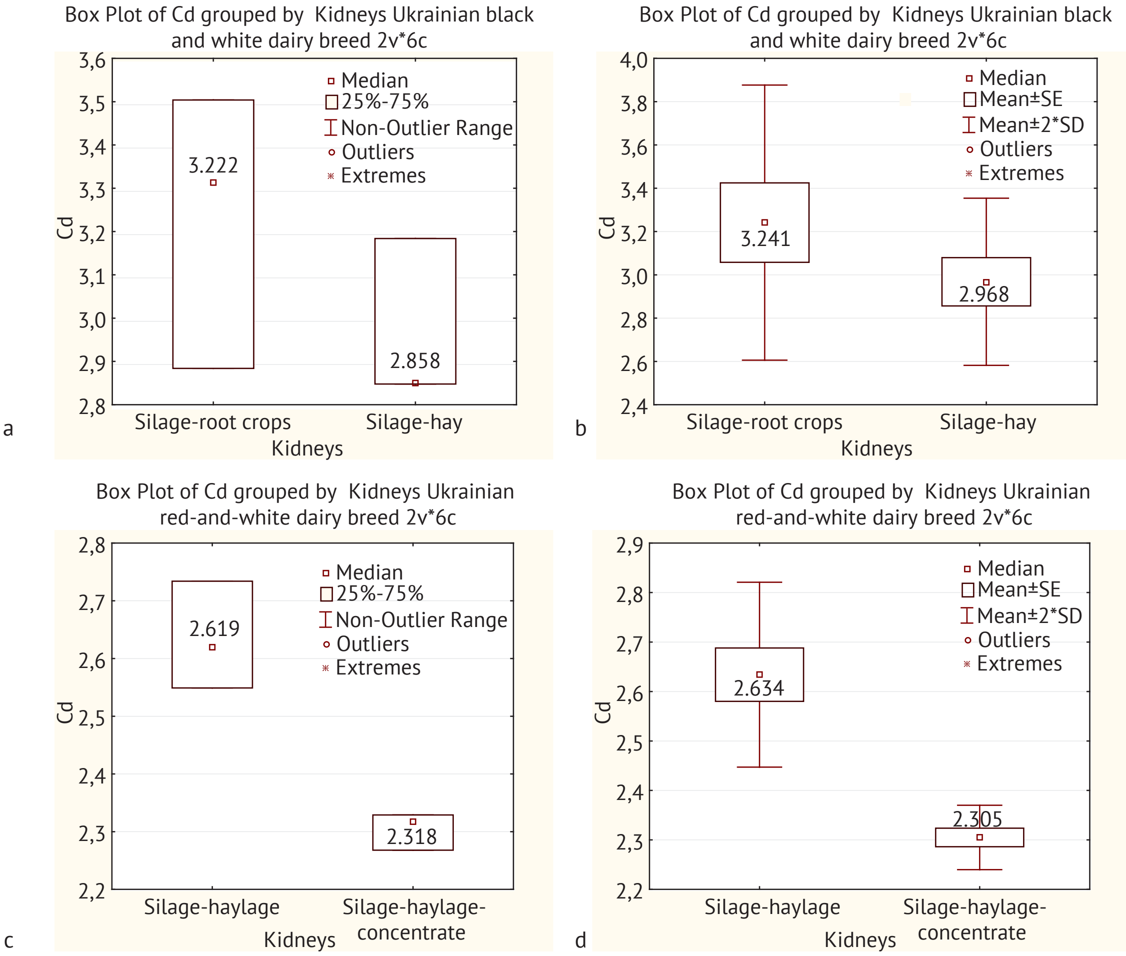

***Figure 1**. Diagrams of mean values and quartile plots of Cd content in the kidneys (mg/kg) of cows from the first control group*
***Note:** a – Black-and-White cows fed a silage-root crop diet; b – Black-and-White cows fed a silage-hay diet; c – Redand-White cows fed a silage-haylage diet; d – Red-and-White cows fed a silage-haylage-concentrate diet*
***Source:** developed by the author*

Analysis of muscle tissue for cadmium content showed that the highest concentration of the pollutant was found in Ukrainian Black-and-White Dairy cows fed a silage-hay diet (0.125 ± 0.026 mg/kg) and a silage-root crop diet (0.140 ± 0.006 mg/kg), compared with Ukrainian Red-and-White Dairy cows receiving silage-haylage-concentrate diets (0.094 ± 0.008 mg/kg) and silage-haylage diets (0.115 ± 0.020 mg/kg). The highest lead concentration in muscle tissue was also detected in Black-and-White cows: 1.472 ± 0.065 mg/kg under the silage-hay diet and 1.691 ± 0.092 mg/kg under the silage-root crop diet. In Ukrainian Red-and-White Dairy cows, the corresponding values were lower, amounting to 1.083 ± 0.008 mg/kg under the silagehaylageconcentrate diet and 1.264 ± 0.067 mg/kg under the silage-haylage diet.

The concentration of heavy metals, particularly cadmium and lead, in the liver, kidneys, muscle tissue, bones, spleen, heart and lungs of animals is one of the key indicators of pollutant intake into the organism via feed. The increased values of these indices indicate that there is a risk of consumption of feed based on plants grown in ecotoxicant-polluted soils. Table 7 shows the cadmium and lead content in different types of diets for Ukrainian Black-and-White and RedandWhite Dairy cows per 1 kg of dry matter.

***Table 7**. Content of toxic heavy metals in diets of different feeding types for cows (mg per 1 kg of dry matter)*

Breed	Feeding type	Cadmium content, mg/kg	Lead content, mg/kg
Black-and-White	Silage-root crop	2.177-2.833	49.567-58.370
	Silage-hay		
Red-and-White	Silage-haylage	1.098-1.271	31.728-34.746
	Silage-haylage-concentrate		

***Source:** developed by the author*

Cadmium and lead levels were higher in the basal diets of the silage-root crop and silage-hay feeding types (2.177-2.833 mg/kg and 49.567-58.370 mg/kg, respectively) of the Ukrainian Blackand-White Dairy breed compared to the silage-haylage and silage-haylage-concentrate ones (1.098-1.271 mg/kg and 31.728-34.746 mg/kg, respectively) of the Ukrainian Red-and-White Dairy breed, in the case of 1 kg dry matter of the feed mixture. The premix and biological preparation used in the experiment contributed to a reduction in Cd and Pb levels in the kidneys, liver, spleen, lung and muscle tissues, heart and bones. In the experimental Ukrainian Black-and-White Dairy cows receiving the silage-root crop diet, the greatest reduction in cadmium content was observed in the kidneys, averaging a 2.5-fold decrease in the second experimental group and a 3.6-fold decrease in the third experimental group compared with the first control group. Cd content in the kidneys decreased from 3.241 ± 0.318 mg/kg in the first control group to 1.294 ± 0.033 mg/kg in the second experimental group and 0.903 ± 0.011 mg/kg in the third experimental group ($p < 0.001$) (Table 8).

***Table 8**. Reduction of cadmium content in the kidneys, mg/kg*

Breed	Feeding type	I	II	III
BlackandWhite	Silage-root crop	3.241 ± 0.318	1.294 ± 0.033	0.903 ± 0.011
	Silage-hay	2.968 ± 0.193	0.884 ± 0.015	0.701 ± 0.013
Red-and-White	Silage-haylage	2.634 ± 0.093	0.831 ± 0.061	0.695 ± 0.026
	Silagehaylageconcentrate	2.305 ± 0.033	0.721 ± 0.027	0.563 ± 0.056

***Source:** developed by the author*

In the second experimental group, over the 120-day experimental period, it was not possible to reduce the Cd content to the permissible limit using the mineral-vitamin premix "MP-A" alone. In the other samples of the internal organs and tissues studied, among the specimens taken from animals of both breeds, the amounts of cadmium in the second and third experimental groups were within the normal values. The administration of the premix had a positive effect, reducing Cd content in muscle tissue in the second and third experimental groups by 66.4%-69.2% compared with the first control group, which in the long term supports the application of technological approaches for the production of environmentally safe beef. A reduction in Cd content was also observed in the liver, spleen, lungs, heart and bone tissue, confirming the beneficial effect of the "MP-A" premix and the "BP-9" biological preparation on the animals' organism. No statistically significant differences in the reduction of cadmium content in lung, heart and muscle tissues were identified between cows of the second and third experimental groups of the Ukrainian BlackandWhite and Red-and-White Dairy breeds; however, the third experimental group demonstrated more favourable values ($p < 0.001$). Therefore, in order to alleviate the intoxication of the organs (the most severe Cd intoxication occurred in the kidneys and liver), a subcutaneous injection of the biological preparation was needed.

The mineral-vitamin premix and the biological preparation demonstrated a stronger antitoxic effect in Ukrainian Red-and-White Dairy cows fed silage-haylage and silage-haylage-concentrate diets. The Cd content in the second and third experimental groups was reduced to the greatest extent. The second and third experimental groups of both breeds complied with maximum permissible concentrations of the pollutant ($p < 0.001$). The reduction in cadmium levels in muscle tissue was most pronounced, compared with the second and third experimental groups, in Ukrainian Black-and-White Dairy cows fed silage-root crop and silage-hay diets. Thus, the decrease was 4.65.5 times in the group of cows that received a silage-haylage diet, 4.1-5.5 times in the group of cows that received a silage-haylage-concentrate diet, and 3.0-3.3-fold in the group of animals that received a silage-root crop diet, and 4.0-4.5-fold in the group of animals that received a silage-hay diet.

In this regard, a significant decrease in the amount of Cd content in the kidney samples is also noted: 3.2-3.8-fold in Ukrainian Red-and-White Dairy cows fed a silage-haylage diet, 3.2-4.1-fold in Ukrainian Red-and-White Dairy cows fed a silage-haylage-concentrate diet and 2.5-3.6-fold in Ukrainian Black-and-White Dairy cows fed a silage-root crop diet and 3.4-4.2-fold in Ukrainian Black-and-White Dairy cows fed a silage-hay diet. No statistically significant differences were found in cadmium content in the muscle tissue, liver, spleen, lungs, heart, and bones of experimental cows between the second and third experimental groups fed silage-haylage and silagehaylage-concentrate diets. The results of the experiment indicate the appropriateness of applying technological approaches involving the administration of the antitoxic premix "MP-A" and injection of the biological preparation "BP-9" in dairy cows fed silage-haylage and silagehaylage-concentrate diets, regardless of breed, as confirmed by the reduction in toxic heavy metal content in the organism. The intensity of Pb removal from the cows' organism was also affected by the pollutant concentration in the diet of experimental animals:

the maximum amount of lead in feed was registered in the diet of Ukrainian Black-and-White Dairy cows fed the silage-root crop and silage-hay diet, and the minimum was in the silage-haylage and silage-haylage-concentrate diet of Ukrainian Red-and-White Dairy cows (Table 9).

***Table 9**. Reduction of lead content in the kidneys, mg/kg*

Breed	Feeding type	I	II	III
BlackandWhite	Silage-root crop	4.522 ± 0.564	0.931 ± 0.019	0.851 ± 0.010
	Silage-hay	4.387 ± 0.092	0.804 ± 0.010	0.735 ± 0.037
Red-and-White	Silage-haylage	3.981 ± 0.274	0.772 ± 0.025	0.639 ± 0.055
	Silagehaylageconcentrate	3.452 ± 0.017	0.785 ± 0.032	0.721 ± 0.014

***Source:** developed by the author*

The level of lead in the analysed samples of internal organs and tissues was significantly affected by the feeding regime; it provided the most significant removal of this contaminant in Ukrainian Red-and-White Dairy cows on a silage-haylage diet (66%-86.4% of the average) and 63.1%-88% in the case of the silage-haylage-concentrate diet ($p < 0.001$), which is of great significance. None of the experimental groups reached the permissible limits of the contaminant's level using only the mineral-vitamin premix, though the inclusion of this compound in the "MP-A" feed premix supplied to the cows of both breeds without the introduction of the phytobiological preparation resulted in a consistent decrease trend of Pb levels in their bodies, regardless of the feeding regime ($p < 0.001$). Using the herbal extract preparation caused stimulation of circulatory, nervous and endocrine system activity, intensification of blood supply to the lungs and removal of Pb from the lungs by 71.6%-80.7% in Ukrainian Black-and-White Dairy cows fed a silage-root crop diet, by 70.7%-83.3% in those fed a silage-hay diet, by 67.7%-86.4% in Ukrainian Red-and-White Dairy cows fed a silage-haylage diet, and by 63.1%-88% in those receiving a silagehaylageconcentrate diet as compared with the first control groups ($p < 0.001$). The type of feeding had a greater effect on the level of ecotoxicants in the internal organs and tissues of cows than the breed of cattle, even in the conditions of using modern technological approaches for obtaining environmentally safe cattle products. The obtained results are consistent with the findings of Y. Akar *et al.* (2018) and I. Tahir & K.A. Alkheraije (2023), who reported that the kidneys and liver are target organs for heavy metal toxicity. Organs such as the lungs, spleen, heart, bone and muscle tissue are capable of accumulating significant amounts of ecotoxicants, particularly highly hazardous ones such as cadmium and lead. This requires further study, in particular, on different breeds of cattle used for milk production.

Researchers from Mongolia, B. Bataa *et al.* (2021), reported maximum lead concentrations in cattle liver at 0.349 mg/kg and in kidneys at 1.08 mg/kg, with minimum levels of 0.2 mg/kg and 0.25 mg/kg, respectively. It follows that this level is much lower than in the presented study, when it was 4.387-4.522 mg/kg and 3.452-3.981 mg/kg, respectively. As for the accumulation of these elements in the internal organs, the authors explained that this occurs due to environmental factors, in which animals are located in areas with an anthropogenic environmental impact. The established regularities of cadmium and lead accumulation in the organs of cattle are in line with the concept of biogeochemical migration of heavy metals in the "soil-plant-animal" system, where the level of their bioavailability and degree of accumulation depends on the physicochemical properties of the soils and feed (Alloway, 2013). According to M.J. Canty *et al.* (2014), 15% of soil in Ireland exceeded the EU norm (1 mg/kg for cadmium) for Cd in soil. Cd concentrations in kidneys ($n = 393$) ranged from 0.040 to 8.630 mg/kg of fresh weight, whereas As, Hg, and Pb concentrations were comparatively low.

Under the conditions of the present study, Cd concentrations in the kidneys ($n = 3$) of cows from the first control groups of the Ukrainian Black-and-White and Red-and-White Dairy breeds ranged from 2.305 to 3.241 mg/kg fresh weight. By comparison, Irish researchers reported an upper cadmium concentration limit that was almost 2.7 times higher (8.630 mg/kg versus 3.241 mg/kg), which was attributed to a higher level of soil contamination and, consequently, of feed contamination in diets. Lead concentrations reported by those authors were relatively low, whereas in the present experiment, Pb concentrations in the kidneys ($n = 3$) of cows from the first control groups of both breeds ranged from 3.452 to 4.522 mg/kg fresh weight. According to M.J. Canty *et al.* (2014), as for the weighted proportion of animals with a high level of cadmium concentration in the kidneys (≥1 mg/kg), according to estimates, this indicator is at the level of 11.25% (95% CI: 8.63%-14.53%). In a conducted experiment, the animals of the first control group in the Ukrainian Black-and-White Dairy breed and in the Ukrainian Red-and-White Dairy breed exceeded this indicator for the content of cadmium in the kidneys (≥1 mg/kg). At the same time, in both breeds in the second and third experimental groups, the use of antidotal substances reduced the concentration of cadmium accumulation (<1 mg/kg) ($p < 0.001$), and the optimal results were observed in the third experimental groups – 0.563-0.695 mg/kg in Ukrainian Red-and-White Dairy breed cows fed silage-haylage-concentrate and silage-hay diets, respectively, and 0.7010.903 mg/kg in Ukrainian Black-and-White Dairy breed cows fed silage-hay and silage-root crop diets, respectively. Ukrainian Red-and-White Dairy breed cows showed the best results.

According to M.J. Canty *et al*. (2014), the significant predictors of high kidney Cd concentrations were soil Cd, animal age, and the province; breed was not a significant predictor. It was estimated that at a soil Cd level of 1.5 mg/kg, the age threshold required to not exceed 1 mg/kg Cd in kidneys for the majority of the animals would be approximately 3 years in Connacht, >4 years in Ulster, and >5 years in Leinster and Munster. In areas of Ireland with naturally elevated soil Cd levels, kidney cadmium concentrations in cattle may exceed the current EU maximum permissible limit of 1 mg/kg in older animals. The kidneys of most cattle under three years of age would comply with EU requirements. In the present study, the age of the animals was 65 months (over 5 years), which objectively implies prolonged accumulation of cadmium and lead not only in the kidneys but also in other organs and tissues. Given the low efficiency of cellular elimination mechanisms for these pollutants, as well as their ability to persist in depot tissues (particularly the liver, kidneys and intestines), gradual accumulation occurs within the organism. As a result, older animals exhibit elevated concentrations of heavy metals in the liver and kidneys even under relatively low levels of exposure via feed and water (Nriagu *et al*., 2009).

The highest Cd concentrations in the topsoil layer in Europe have been recorded in Ireland, England, the Western Alps and southern France, the Belgian-German border region, southern Sardinia, eastern Italy, Slovenia, Croatia, Albania and Greece. The elevated levels of Cd in most of these areas are attributed to the intensive application of phosphate fertilisers and sewage sludge in agriculture, except Ireland, southern Sardinia, Poland and the district of Goslar in Germany, where naturally high Cd is recorded (Pan *et al*., 2010). The Czech researchers J. Drapal *et al*. (2021) analysed cadmium concentration in the muscle, liver and kidneys of cattle of different ages. In cattle older than two years, higher mean cadmium concentrations were observed in the liver (0.10 mg/kg) and kidneys (0.62 mg/kg) compared with cattle under two years of age, where values were 0.06 mg/kg in the liver and 0.24 mg/kg in the kidneys. These values were considerably lower than those obtained in the present research.

Thus, the higher concentrations of cadmium and lead in the internal organs and tissues of cows of different Ukrainian dairy breeds used in the experiment are determined not by breed type, but primarily by the level of pollutant intake through feed of different dietary types; however, a breed-related effect is also present. The accumulation of ecotoxicants in the kidneys, liver, lungs, spleen, heart, and bone and muscle tissues can be counteracted solely by administering specially selected antidotal compounds (such as mineral-vitamin premixes) or adopting environmentally safe feeding systems with an increased share of low-pollutant feeds. In addition, the impact of premixes can be augmented via the cellular-level introduction of biological preparations from medicinal plant extracts aimed at intensifying the protective functions of the organism and promoting the synthesis of specific metal-binding proteins (metallothioneins). In the experiment on the production of environmentally safe cow's milk, the most favourable results were achieved when using silagehaylage and silage-haylage-concentrate diets for Ukrainian Red-and-White Dairy cows. These outcomes may also be influenced by the genetic features that determine the character of metabolism in productive livestock exposed to toxicants from a group of heavy metals. Under the conditions of the conducted study, aimed at producing environmentally safe cow's milk, the most effective feeding systems were the silage-haylage and silage-haylage-concentrate diets used for Ukrainian Red-and-White Dairy cows. Likely, genetically determined metabolic features in productive animals under heavy metal intoxication may have additionally influenced the observed results.

CONCLUSIONS

The internal organs and tissues of dairy cows receiving feed with elevated concentrations of heavy metals (Cd and Pb) accumulate these elements. Cattle of the Ukrainian Black-and-White Dairy breed accumulated the highest levels of cadmium and lead in their kidneys (2.968-3.241 mg/kg and 4.3874.522 mg/kg), the liver (0.701-0.752 mg/kg and 1.731-1.865 mg/kg) compared to animals of the Ukrainian Red-and-White Dairy breed in the kidneys (2.305-2.634 mg/kg and 3.4523.981 mg/kg), liver (0.611-0.683 mg/kg and 1.607-1.694 mg/kg), which is due to a higher intake of pollutants from the feed in the main diets (2.177-2.833 (Cd) mg/kg and 49.56758.370 (Pb) mg/kg of dry matter in the feed, compared with 1.098-1.271 (Cd) mg/kg and 31.728-34.746 (Pb) mg/kg), and the type of feeding, rather than breed-specific characteristics. Dairy cows of the Ukrainian Red-and-White breed fed on the basis of silage-haylage and silagehaylageconcentrate had lower concentrations of cadmium and lead in internal organs, bones, and muscles of the cow. Greater influence on the accumulation of the investigated hazardous ecotoxicants in the internal organs and tissues of cows of different breeds may be exerted, first and foremost, by environmental contamination factors affecting atmospheric air, soil, feed and water. Physiological factors are also important, including substantial differences in body weight, milk productivity, stage of lactation and animal age, among others, as well as the influence of breedrelated factors associated with genetic features of metabolism, differences in the intensity of accumulation or elimination of toxicants under varying housing and feeding conditions. These should be subject to a separate investigation for a breed. In future, the correlation and regression analyses of the heavy metal content in the food of feeding diets of different types and in the organs and muscles of dairy cattle should be performed.

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CONFLICT OF INTEREST

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Накопичення кадмію та плюмбуму в органах та тканинах дійних корів залежно від породи і раціону

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Анотація. Моніторинг агроекосистем в умовах повномасштабної війни вказує на великі техногенні навантаження, посилення забруднення довкілля важкими металами, в тому числі токсичними і контамінантними Cd та Pb. Метою досліджень був аналіз вмісту кадмію та плюмбуму у нирках, печінці, легенях, серці, селезінці, кістковій і м'язовій тканинах дійних корів в залежності від породи, виду раціону в умовах технології виробництва екологічно безпечного коров'ячого молока. В господарствах Лісостепової ґрунтово-кліматичної зони України було проведено досліди на дійних коровах різних порід з контрольним забоєм в кінці експерименту. Найбільшу концентрацію Cd було встановлено у нирках корів української чорно-рябої молочної породи з силосно-сінним раціоном 2,968 ± 0,193 мг/кг та силосно-коренеплодним 3,241 ± 0,318 мг/кг, аналогічно по Pb з силосно-сінним типом годівлі 4,387 ± 0,092 мг/кг та силосно-коренеплодним 4,522 ± 0,546 мг/кг. Аналіз м'язової тканини на вміст Cd показав найбільшу концентрацію у тварин української чорно-рябої молочної породи з силосно-сінним раціоном 0,125 ± 0,026 мг/кг та силосно-коренеплодним 0,140 ± 0,006 мг/кг. Концентрація Pb у м'язовій тканині теж найбільшою встановлена у корів української чорно-рябої молочної породи 1,472 ± 0,065 мг/кг, де згодовувався силосно-сінний раціон і 1,691 ± 0,092 мг/кг силосно-коренеплідний. Найбільшу концентрацію Cd та Pb у нирках, печінці, легенях, селезінці, серці, кістках та м'язовій тканині встановлено у корів української чорно-рябої молочної породи в порівнянні з тваринами української червоно-рябої молочної породи, що обумовлене більшим надходженням полютантів з кормами основних раціонів, типом годівлі, ніж породними особливостями. Отримані дані можуть бути використані при розробці рекомендацій щодо вибору типів раціонів і технологій годівлі дійних корів з метою зменшення акумуляції важких металів у внутрішніх органах і тканинах, а також для підвищення екологічної безпечності коров'ячого молока та продуктів його переробки

Ключові слова: екотоксиканти; корми; тип годівлі; важкі метали; продуктивні тварини; агроекосистеми

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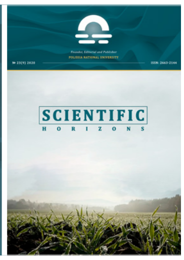

The effect of manure application timing, mineral fertilisers and planting density on potato growth and development

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Abstract. Increasing potato production should be achieved not only by expanding the cultivated area, but primarily by increasing crop yields. To improve potato productivity, the rational use of local organic fertilisers, alongside mineral fertilisers, is of considerable importance. Therefore, this study aimed to investigate the growth and development of potato plants in relation to the timing of manure application in combination with mineral fertilisers and planting density. Field experiments were conducted using a systematic design, with treatments arranged in tiers and replicated three times. The smallest number of stems was formed under the application of mineral fertilisers at a rate of $N_{60}P_{120}K_{60}$ and a planting scheme of 70×25 cm

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(5.8 stems per plant). The largest number of stems was observed when 40 t/ha of manure was applied during autumn ploughing in combination with mineral fertilisers at a rate of $N_{90}P_{120}K_{60}$ (7.2 stems per plant), as well as when manure was applied after spring reploughing of autumn-ploughed soil, followed by planting according to the 70×35 cm scheme (7.4 stems per plant). The number of stems increased with an expanded feeding area by 0.1-0.3 stems. On average, over three years, spring application of 40 t/ha of manure on the $N_{60}P_{120}K_{60}$ background increased the number of leaves to 50.6, compared with 41.3 leaves under $N_{90}P_{120}K_{60}$. The weight of the haulm of a single plant varied depending on the feeding area, the year of cultivation and the timing of manure application. When the feeding area was expanded to 70×35 cm, the weight of the haulm increased. The highest average haulm yield over three years (61.20 t/ha) was obtained when manure was applied during autumn ploughing, and potatoes were planted according to the 70×25 cm scheme. With the expanded feeding area, haulm yield was 50.20 t/ha, which was 11 t/ha lower. A similar pattern was observed for the other experimental treatments. Based on the results of field experiments conducted under production conditions, recommendations can be developed for producers on the most efficient use of organic and mineral fertilisers to increase potato productivity

Keywords: field research; yield improvement; ploughing; plant haulm weight

INTRODUCTION

The West Kazakhstan region faces complex challenges in increasing potato productivity, making it particularly important to meet the regional demand for potatoes. Potatoes are one of the most important food crops in the region and play a significant role in ensuring food security and a stable supply of agricultural products to the population. At the same time, unstable climatic conditions, insufficient soil fertility and inefficient fertiliser use reduce the efficiency of potato production. Therefore, the development of scientifically grounded approaches to optimising fertilisation systems and planting density under the soil and climatic conditions of West Kazakhstan is highly relevant.

Research by W. Zhong *et al.* (2025) indicated that mineral nutrition is one of the most effective factors influencing plant growth and productivity. According to T. Salikhov *et al.* (2023), regulation of the intensity of nutrient supply through fertiliser application changes the activity and even the direction of biochemical reactions in plants. A.K. Sandhu *et al.* (2024) reported that phosphorus application improved potato yield even when soil-test phosphorus was within the high range. However, A.P.P. Ravensbergen *et al.* (2024) emphasised that improvements in yield and fertiliser-use efficiency must be achieved on a field-by-field basis. Furthermore, it can be concluded that frequent field monitoring combined with crop growth modelling is an effective way to assess yield-gap variability and obtain detailed information on the factors explaining this gap at the field level.

Yield structure and the ratio between the vegetative and productive parts of plants are important indicators for assessing the effect of fertilisers on potato productivity. H. Xue *et al.* (2024) found that using nitrogen alone or in combination with urea can reduce both the total nitrogen application rate and the frequency of application. However, according to Xu *et al.* (2023), increasing fertiliser application rates without considering nutrient balance and the physiological requirements of crops can lead to greater unproductive losses of mineral nutrients from the soil and fertilisers, as well as to environmental pollution. At the same time, the availability and balance of nutrients in agriculture determine crop yields and gross agricultural production. F. Zhao *et al.* (2024) showed that reducing excessive water evaporation during periods of low rainfall, improving drainage during periods of high rainfall, applying fertilisers and planting potatoes at optimal times can contribute to higher potato yields. The results of the study by B. Almunqedhi *et al.* (2025) confirm that poultry manure improves growth, tuber quality and yield because it contains nutrients such as nitrogen, phosphorus and potassium.

Q.G. Liang *et al.* (2026) reported that optimised nitrogen (N) application and planting density can enhance sweet potato yield. However, the agronomic mechanisms underlying their effects on photosynthetic efficiency and carbohydrate metabolism in sweet potato remain unclear. Their results indicate that reduced nitrogen fertilisation combined with dense planting creates a more suitable canopy structure for light distribution at the population level and optimises light and carbon-use efficiency at the individual plant level, thereby improving storage-root yield and the commercial characteristics of sweet potato. Research by D. Ademe *et al.* (2024) found that late planting and higher nitrogen rates increased tuber yield in the near-term climate period. However, in the mid-century climate period, early planting of both medium- and long-maturity varieties with higher nitrogen rates showed potential adaptive benefits, despite their negative impact on yield under the current climate. This result highlights the distinction between optimal management under current conditions and practices that are truly adaptive to climate change. T. Tekalign *et al.* (2023) reported that the adoption of improved potato varieties increases food security by an average of 324.5 kcal per adult per day. The findings showed that the adoption of improved potato varieties had a positive impact on household resilience to food insecurity. According to Y. Xing *et al.* (2022), potato productivity is generally influenced by water and fertiliser use, although the requirements for these factors vary depending on soil type and potato variety. Potato tuber yield was significantly correlated with soil-available potassium, the number of soil actinomycetes, soil catalase activity and soil sucrase activity (SSA). The effect of manure application timing in combination with mineral fertilisers and planting density on weed infestation in potato plantations was established, although this area remains insufficiently studied. Therefore, the purpose of the scientific experiment was to determine how the timing of manure application in combination with mineral fertilisers and planting density affects the growth and development of potatoes in the West Kazakhstan region.

MATERIALS AND METHODS

Phenological observations of the growth and development of Nevsky potato plants were conducted at Tuaytai farm in Chingirlau District of West Kazakhstan region, during the 2017-2019 growing seasons. The study was based on field data collected in 2017-2019. As of 2026, newer observations are not yet available because similar studies are currently being conducted in other soil and climatic regions of Northern Kazakhstan. The research methods included descriptive method, an integrated approach and field experimentation. The experiments were established using a systematic design, with treatments arranged in tiers and replicated three times.

The total plot area was 84 m^2, the recorded plot area was 56 m^2, and each treatment was replicated three times. The following observations, measurements and analyses were conducted during the experiments. Before planting, total nitrogen was determined by the Kjeldahl method, available phosphorus by the Machigin method, available potassium by the Protasov method and pH in an aqueous extract in the 0-30 cm soil horizon (Research methods for potato crops, 1967). The main nutrients in the manure were determined in samples collected before soil application. The manure was ploughed in immediately after application. The experimental plot was divided into individual plots in the autumn. The required amount of manure was weighed and spread manually across the plots.

The determination of available forms of nitrogen, phosphorus and potassium in the soil was performed at several stages: before planting, during emergence, during flowering and before harvesting. Weed infestation was determined using a quantitative weight-based method. Soil moisture in the 0-50 cm layer was measured 3-4 days after watering, and the amount of productive moisture was expressed in millimetres of water depth. Its reserves were calculated according to the methodology described in Research methods for potato crops (1967).

Phenological observations were conducted daily in all experimental treatments throughout the growing season. The onset of each phase was determined based on the number of plants reaching that phase in each plot. The following phases were recorded: beginning of emergence, full emergence, beginning of budding, full budding, beginning of flowering, full flowering and beginning of senescence. Plant density was calculated after emergence and before harvesting in all plots across all experimental replicates. Plant height was measured every 10 days by assessing 10 consecutive plants in each plot across all replicates.

In addition, the haulm of 10 typical plants from each plot was weighed in all treatments at the beginning of budding, at flowering and during dynamic digging. During this process, the assimilation surface area of the leaves was determined using the punch method, according to Research methods for potato crops (1967). After weighing the haulm, the leaves of each plant were removed, and 100 fresh leaves were taken from each plant. Using a drill of known diameter, 100 leaf discs were punched out and weighed on a technical scale. The leaf area of a single plant was determined by the ratio of total leaf weight to the weight of the leaf discs, and then the leaf area per hectare was converted to m^2. Leaf area per plant was determined using the formula:

$$M = \frac{P}{P_1 \times H \times K}, \qquad (1)$$

where M is the leaf area per plant; P is the mass of leaves in the sample; P_1 is the mass of the leaf discs punched from the leaves; K is the area of the punched discs; H is the number of leaves taken for analysis.

The intensity of photosynthesis was determined by changes in the dry weight of leaves, as described in Research Methods for Potato Crops (1967). For the experiment, leaves with the most symmetrical structure were selected. One half of each leaf was removed, while the other half, together with the petiole, was left on the plant. The cut halves were incubated for 15-30 minutes. The leaves were placed in water or wrapped in a damp cloth to achieve complete saturation. They were then dried with filter paper and placed upside down on a smooth cork surface to expose the veins more clearly. At least 100 leaf discs were cut out using a sharp drill. These discs were divided into a series of parallel samples, placed in tared glass containers and dried to a constant weight. The initial weight per unit leaf area was obtained by dividing the weight by the area. At the end of the exposure period (after 4-6 hours), the remaining leaf halves were removed, and the weight per unit area was determined in the same manner. The weight gain observed during the exposure period was calculated per unit area per hour.

To determine photosynthesis, a dark control was introduced. In addition to the experimental samples, parallel leaf samples were taken from the same plant and placed in darkness. Both the control and experimental leaves were cut in half, and one half was covered with an opaque paper cap. Both halves were treated in exactly the same manner as described above, with weight loss per unit area taken into account rather than weight gain. By adding the loss of substance during the experiment, caused by respiration and translocation, to the gain, a substantially more accurate assimilation value was obtained. The photosynthesis rate was calculated using the following formula:

$$I = \frac{(a_1 - a) + (a - a_2)}{r}, \quad (2)$$

where I is the rate of photosynthesis, mg dry matter/hour; a is the initial leaf weight, mg; a_1 and a_2 are the weights of leaves exposed to light and darkness, respectively, mg; r is the exposure time, hours.

Experimental design:

1. $N_{60}P_{120}K_{60}$
2. $N_{90}P_{120}K_{60}$
3. 40 t/ha manure applied during autumn ploughing + $N_{60}P_{120}K_{60}$
4. 40 t/ha manure applied during autumn ploughing + $N_{90}P_{120}K_{60}$
5. 40 t/ha manure applied on frozen soil + $N_{60}P_{120}K_{60}$
6. 40 t/ha manure applied on frozen soil + $N_{90}P_{120}K_{60}$
7. 40 t/ha manure applied on snow during winter + $N_{60}P_{120}K_{60}$
8. 40 t/ha manure applied on snow during winter + $N_{90}P_{120}K_{60}$
9. 40 t/ha manure applied before spring re-ploughing of autumn-ploughed soil + $N_{60}P_{120}K_{60}$
10. 40 t/ha manure applied before spring re-ploughing of autumn-ploughed soil + $N_{90}P_{120}K_{60}$

Planting scheme: 70×25 cm and 70×35 cm.

Manure was applied in the autumn on 10-15 September before ploughing the fallow land, on 2530 November on frozen fallow land, on 5-7 January on shallow snow and in the spring on 2025 April before ploughing the fallow land. The composition of manure changed little over the years. The following types of mineral fertilisers were used: ammonium nitrate, double superphosphate and potassium chloride. Mineral fertilisers were applied during autumn ploughing. The required amount of manure was weighed and spread manually across the plots. The main nutrients in the manure were determined in samples taken before application to the soil. In the autumn, the manure was ploughed in immediately after application. The development of potato plants in $N_{60}P_{120}K_{60}$ potato plantings was recorded in accordance with Research methods for potato crops (1967). The study was conducted in accordance with the principles of environmental safety set out in the Convention on the Conservation of European Wild Flora and Fauna and Natural Habitats (1979). All agronomic practices and field experiments were carried out in a manner that minimised negative impacts on the surrounding environment and preserved the balance of natural ecosystems.

RESULTS

Field observations showed that mineral fertiliser rates and manure application dates affected the formation of stems and leaves in potato plants (Table 1).

***Table 1.** Potato development depending on fertiliser application and planting density*

Planting scheme	Manure application dates	Number of stems per plant					
		stems			leaves		
		2017	2018	2019	2017	2018	2019
70×25 cm	$N_{60}P_{120}K_{60}$	5.7	5.7	6.0	148.4	153.6	157.4
	$N_{90}P_{120}K_{60}$	5.9	6.0	6.4	160.1	164.8	169.5
	40 t/ha manure applied during autumn ploughing + $N_{60}P_{120}K_{60}$	6.7	6.9	7.2	192.4	200.7	208.6
	40 t/ha manure applied during autumn ploughing + $N_{90}P_{120}K_{60}$	6.9	7.1	7.6	201.1	202.5	212.4
	40 t/ha manure applied on frozen soil + $N_{60}P_{120}K_{60}$	6.4	6.5	6.7	160.1	166.6	172.4
	40 t/ha manure applied on frozen soil + $N_{90}P_{120}K_{60}$	6.6	6.8	6.9	169.4	172.8	180.6
	40 t/ha manure applied on snow during winter + $N_{60}P_{120}K_{60}$	6.3	6.4	6.6	165.8	173.9	177.8
	40 t/ha manure applied on snow during winter + $N_{90}P_{120}K_{60}$	6.4	6.5	6.7	172.2	175.7	180.4
	40 t/ha manure applied before spring re-ploughing of autumn-ploughed soil + $N_{60}P_{120}K_{60}$	6.9	7.0	7.2	194.9	205.9	210.5
	40 t/ha manure applied before spring re-ploughing of autumn-ploughed soil + $N_{90}P_{120}K_{60}$	7.1	7.2	7.4	197.0	206.7	214.8
70×35 cm	$N_{60}P_{120}K_{60}$	5.8	5.9	6.1	152.2	162.6	166.8
	$N_{90}P_{120}K_{60}$	6.2	6.4	6.6	155.9	172.4	174.8
	40 t/ha manure applied during autumn ploughing + $N_{60}P_{120}K_{60}$	6.9	7.2	7.3	202.6	202.8	216.2
	40 t/ha manure applied during autumn ploughing + $N_{90}P_{120}K_{60}$	7.2	7.4	7.8	205.8	206.6	220.4
	40 t/ha manure applied on frozen soil + $N_{60}P_{120}K_{60}$	6.5	6.6	6.8	174.3	182.6	188.8
	40 t/ha manure applied on frozen soil + $N_{90}P_{120}K_{60}$	6.8	6.9	7.0	176.8	194.8	199.4
	40 t/ha manure applied on snow during winter + $N_{60}P_{120}K_{60}$	6.5	6.6	6.9	168.8	190.6	194.7
	40 t/ha manure applied on snow during winter + $N_{90}P_{120}K_{60}$	6.6	6.6	6.9	174.8	195.2	198.5
	40 t/ha manure applied before spring re-ploughing of autumn-ploughed soil + $N_{60}P_{120}K_{60}$	7.1	7.2	7.2	197.0	206.8	218.6
	40 t/ha manure applied before spring re-ploughing of autumn-ploughed soil + $N_{90}P_{120}K_{60}$	7.4	7.4	7.6	199.9	208.6	222.9

***Source:** compiled by the authors*

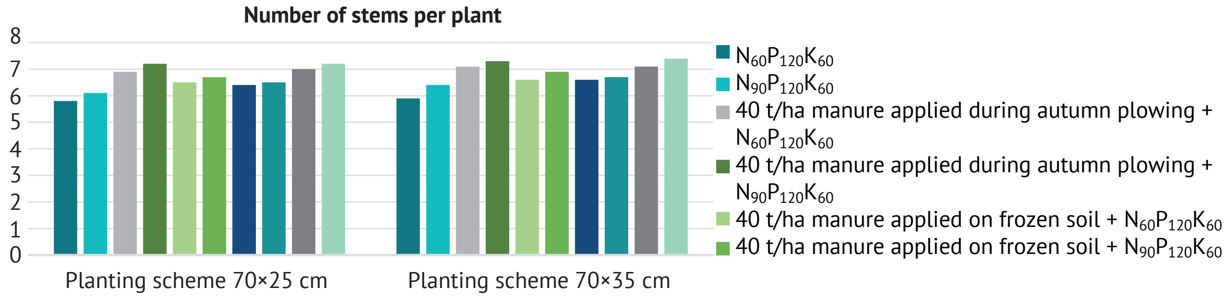

***Figure 1**. Number of stems per plant, averaged over three years*

***Source:** compiled by the authors*

The lowest average number of stems over three years was observed when mineral fertilisers were applied at a rate of $N_{60}P_{120}K_{60}$ (5.8 stems per plant) with a planting scheme of 70×25 cm. The highest number of stems was recorded when 40 t/ha of manure was applied during autumn ploughing in combination with mineral fertilisers at a rate of $N_{90}P_{120}K_{60}$ (7.2 stems per plant), as well as when the same dose was applied before spring re-ploughing of autumn-ploughed soil, with planting according to the 70×35 cm scheme (7.4 stems per plant). A tendency for the number of stems to increase by 0.1-0.3 stems with an expanded feeding area was observed. The largest number of stems in all treatments was recorded in 2019, which was characterised by favourable weather conditions for potato cultivation. These factors also had a significant influence on leaf formation. The largest number of leaves was observed on plants in 2019 because of favourable weather conditions. The difference between the experimental treatments ranged from 9 to 23 leaves per plant. The smallest number of leaves was observed when mineral fertilisers were applied at a rate of $N_{60}P_{120}K_{60}$. When the fertiliser rate was increased to $N_{90}P_{120}K_{60}$, the number of leaves per plant increased by an average of 11.7 over three years. In all treatments with manure application, the number of leaves increased significantly. Thus, in 2017, when 40 t/ha of manure was applied during autumn ploughing in combination with mineral fertilisers at a rate of $N_{60}P_{120}K_{60}$, the number of leaves per plant increased by 44 leaves compared with the control treatment ($N_{60}P_{120}K_{60}$ without manure) and by 52.7 leaves on the $N_{90}P_{120}K_{60}$ background. On average, over three years, spring application of 40 t/ha of manure on the $N_{60}P_{120}K_{60}$ background increased the number of leaves by 50.6, while on the $N_{90}P_{120}K_{60}$ background it increased the number of leaves by 41.3, compared with the same mineral fertiliser rates without manure (Fig. 2).

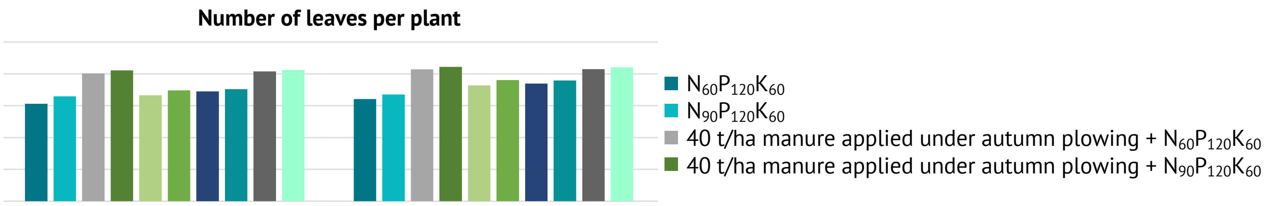

***Figure 2**. Number of leaves per plant, averaged over three years*

***Source:** compiled by the authors*

When manure was applied on frozen soil after autumn ploughing and on snow during winter, fewer leaves were formed. Thus, on average, over three years, when manure was applied on frozen soil on the $N_{60}P_{120}K_{60}$ background, 166.3 leaves per plant were formed, which was 13.2 leaves more than in the control treatment. However, this value was 47.4 leaves lower than when manure was applied during autumn ploughing. On the $N_{90}P_{120}K_{60}$ background, the number of leaves was 9.4 leaves higher than in the control treatment, but 31.1 leaves lower than when manure was applied during autumn ploughing. When manure was applied on snow during winter, the number of leaves increased slightly by 6.2 and 1.9 leaves, but remained significantly lower than when manure was applied during autumn ploughing or in spring before re-ploughing autumn-ploughed soil. The mass of the haulm of a single plant varied depending on the feeding area, the year of cultivation and the timing of manure application (Table 2).

Thus, in 2017, when $N_{60}P_{120}K_{60}$ was applied, the total plant weight was 518.4 g. When $N_{90}P_{120}K_{60}$ was applied, it was 666.5 g, which was 148.1 g higher. When 40 t/ha of manure was applied in combination with the specified fertiliser rates, the total weight was 934.1 g and 993.7 g, respectively, which was 415.7 g and 327.2 g higher, or 80.2% and 49.1% higher, respectively (Fig. 3).

***Table 2**. Haulm weight per plant, depending on fertiliser application and planting density*

Planting scheme	Manure application dates	Total weight of 1 plant, g			Stem weight, g			Leaf mass, g		
		2017	2018	2019	2017	2018	2019	2017	2018	2019
70×25 cm	$N_{60}P_{120}K_{60}$	518.4	528.6	674.8	248.6	255.9	328.2	269.8	272.7	346.6
	$N_{90}P_{120}K_{60}$	666.5	674.2	789.5	300.4	331.4	349.4	363.1	342.8	440.1
	40 t/ha manure applied during autumn ploughing + $N_{60}P_{120}K_{60}$	934.1	984.3	1,184.4	450.0	459.6	583.6	484.1	524.7	600.8
	40 t/ha manure applied during autumn ploughing + $N_{90}P_{120}K_{60}$	993.7	1,003.6	1,218.6	463.2	468.6	594.8	530.5	535.0	623.8
	40 t/ha manure applied on frozen soil + $N_{60}P_{120}K_{60}$	807.5	875.4	907.8	363.4	398.8	431.5	444.1	472.6	476.3
	40 t/ha manure applied on frozen soil + $N_{90}P_{120}K_{60}$	896.4	916.6	964.9	436.1	444.2	452.1	460.3	476.4	512.8
	40 t/ha manure applied on snow during winter + $N_{60}P_{120}K_{60}$	739.7	792.1	814.8	359.4	378.9	388.3	380.3	413.2	426.5
	40 t/ha manure applied on snow during winter + $N_{90}P_{120}K_{60}$	784.5	848.6	902.6	372.2	401.2	448.4	412.3	447.4	454.2
	40 t/ha manure applied before spring re-ploughing of autumn-ploughed soil + $N_{60}P_{120}K_{60}$	894.8	905.4	938.3	432.3	438.1	454.2	462.5	467.3	484.1
	40 t/ha manure applied before spring re-ploughing of autumn-ploughed soil + $N_{90}P_{120}K_{60}$	904.7	941.3	984.6	438.3	462.1	486.4	466.4	479.2	498.2
70×35 cm	$N_{60}P_{120}K_{60}$	598.8	614.2	714.6	275.2	288.4	334.7	323.6	325.8	379.9
	$N_{90}P_{120}K_{60}$	694.2	702.8	796.8	334.0	316.4	375.2	360.2	386.4	421.6
	40 t/ha manure applied during autumn ploughing + $N_{60}P_{120}K_{60}$	964.8	996.4	1,204.5	474.3	461.4	599.4	490.5	535.0	605.1
	40 t/ha manure applied during autumn ploughing + $N_{90}P_{120}K_{60}$	999.6	1,244.3	1,248.4	485.4	714.8	598.6	514.2	529.5	649.8
	40 t/ha manure applied on frozen soil + $N_{60}P_{120}K_{60}$	854.6	898.4	924.4	424.2	442.4	449.5	430.4	456.0	474.9
	40 t/ha manure applied on frozen soil + $N_{90}P_{120}K_{60}$	904.8	966.5	1,001.2	439.9	463.2	475.4	464.9	503.3	525.8
	40 t/ha manure applied on snow during winter + $N_{60}P_{120}K_{60}$	856.7	901.4	983.5	421.6	428.7	481.1	435.1	472.7	502.4
	40 t/ha manure applied on snow during winter + $N_{90}P_{120}K_{60}$	869.5	916.6	998.7	429.5	439.5	488.2	440.0	477.1	510.5
	40 t/ha manure applied before spring re-ploughing of autumn-ploughed soil + $N_{60}P_{120}K_{60}$	944.3	998.3	1,238.6	452.2	464.6	594.3	492.1	533.7	644.3
	40 t/ha manure applied before spring re-ploughing of autumn-ploughed soil + $N_{90}P_{120}K_{60}$	969.5	1,055.4	1,252.4	468.3	501.4	599.9	501.2	554.0	652.5

***Source:** compiled by the authors*

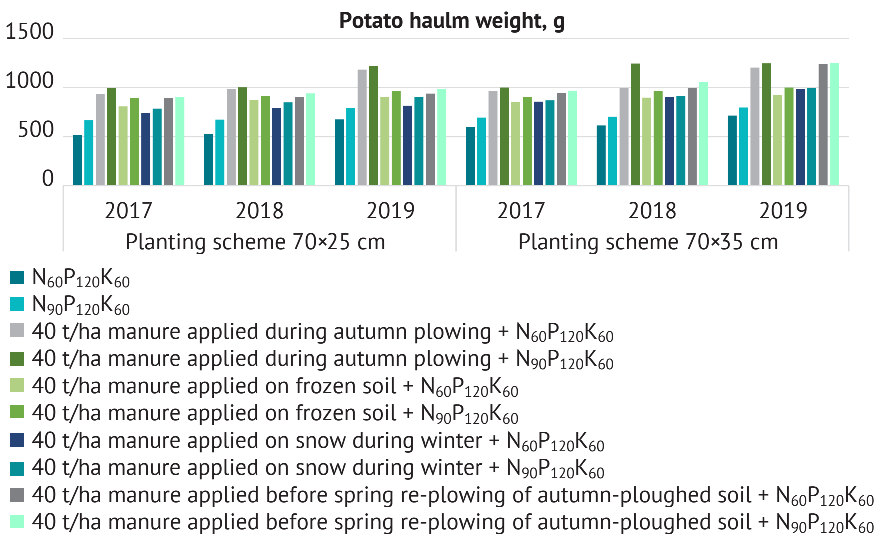

***Figure 3**. Potato haulm weight depending on fertiliser application and planting density, g*
***Source:** compiled by the authors*

When manure was applied on frozen soil after autumn ploughing, plant biomass decreased compared with manure application during autumn ploughing: by 126.6 g on the $N_{60}P_{120}K_{60}$ background and by 97.3 g on the $N_{90}P_{120}K_{60}$ background. When manure was applied on snow during winter, an even greater decrease in plant biomass was observed, at 194.4 g and 209.2 g, respectively. When manure was applied before spring re-ploughing of autumn-ploughed soil, the haulm weight per plant increased compared with application on frozen soil and on snow in winter, but remained lower than with manure application during autumn ploughing: by 39.3 g on the $N_{60}P_{120}K_{60}$ background and by 89.0 g on the $N_{90}P_{120}K_{60}$ background.

Thus, in 2017, when $N_{60}P_{120}K_{60}$ was applied, and potatoes were planted according to the 70×35 cm scheme, haulm weight per plant was 80.4 g higher than with the 70×25 cm scheme. When $N_{90}P_{120}K_{60}$ was applied, it was 27.7 g higher. Application of manure during autumn ploughing led to an increase in haulm weight with the expansion of the feeding area, by 30.7 g and 5.9 g, respectively. This difference in plant biomass formation is probably explained by differences in soil microbiological activity associated with the timing of manure application and planting density. This issue requires further, more detailed study.

A similar pattern of above-ground biomass formation was observed in 2018; however, favourable weather conditions in May and June contributed to the development of greater foliage mass than in 2017. Thus, when $N_{60}P_{120}K_{60}$ was applied, and potatoes were planted according to the 70×25 cm scheme, haulm weight per plant reached 528.6 g, which was 10.2 g higher than in 2017. On the $N_{90}P_{120}K_{60}$ background, the increase was 7.7 g. When 40 t/ha of manure was applied during autumn ploughing, haulm weight increased by 50.2 g and 9.9 g, respectively. When manure was applied on frozen soil after autumn tillage, the increase was 67.9 g and 20.2 g, and when it was applied on snow during winter, the increase was 52.4 g and 64.1 g. When manure was applied before spring re-ploughing of autumn-ploughed soil, the increase was 10.6 g and 36.6 g. However, when potatoes were planted according to the 70×35 cm scheme, haulm weight per plant increased significantly. Thus, when $N_{60}P_{120}K_{60}$ was applied, haulm weight per plant was 85.6 g greater than under denser planting, and when $N_{90}P_{120}K_{60}$ was applied, the increase was 28.6 g. When manure was applied during autumn ploughing, the increase reached 121.1 g and 240.7 g, respectively.

The warm spring and cool summer of 2019 contributed to a substantial increase in above-ground biomass. Thus, when $N_{60}P_{120}K_{60}$ was applied and potatoes were planted according to the 70×25 cm scheme, haulm weight per plant in 2019 exceeded that of 2017 by 156.4 g and that of 2018 by 146.2 g. When $N_{90}P_{120}K_{60}$ was applied, the increase was 123.0 g and 115.3 g, respectively. A pronounced increase in growth was observed when manure was applied. When manure was applied during autumn ploughing on the $N_{60}P_{120}K_{60}$ background, haulm weight in 2019 exceeded that of 2017 by 250.3 g and that of 2018 by 200.1 g. On the $N_{90}P_{120}K_{60}$ background, the increase was 224.9 g and 215.0 g, respectively.

When the feeding area was expanded to 70×35 cm, haulm weight per plant increased. Thus, when manure was applied during autumn ploughing, haulm weight reached 1,204.5 g on the $N_{60}P_{120}K_{60}$ background and 1,248.4 g on the $N_{90}P_{120}K_{60}$ background, which was 20.1 g and 29.8 g higher than under denser planting (70×25 cm). When manure was applied before spring re-ploughing of autumnploughed soil, the increase was 300.3 g and 267.8 g, respectively. The highest haulm weight per plant in 2019 was recorded when 40 t/ha of manure was applied before spring re-ploughing of autumn-ploughed soil (1,252.4 g). A similar pattern was observed for stem mass (Fig. 4). The lowest stem mass was recorded when $N_{60}P_{120}K_{60}$ was applied. In 2017, it was 248.6 g, in 2018 it was 255.9xg, and in 2019 it was 328.2 g. When $N_{90}P_{120}K_{60}$ was applied, the values were 300.4 g, 331.4 g and 349.4 g, which were 51.8 g, 75.5 g and 21.2 g higher, respectively.

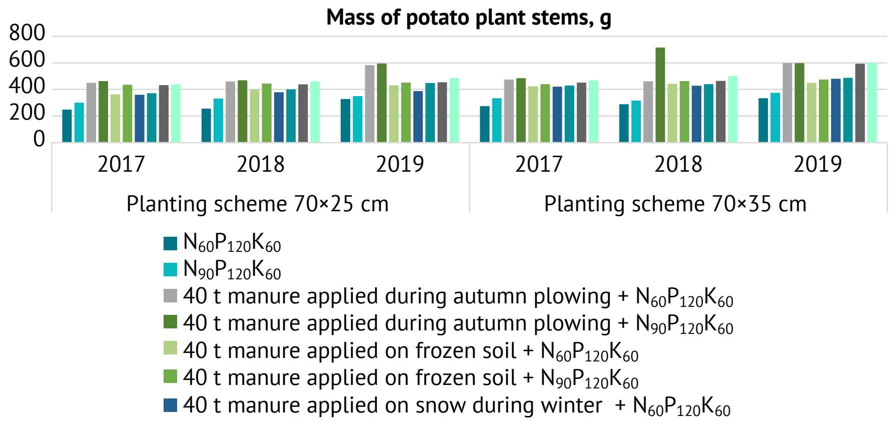

***Figure 4**. Mass of potato plant stems depending on fertiliser application and planting density, g*
Source: *compiled by the authors*

When manure was applied, stem mass increased significantly in all treatments; however, the highest stem mass was observed when manure was applied during autumn ploughing and before spring re-ploughing of autumn-ploughed soil. Thus, when manure was applied during autumn ploughing, stem mass in 2019 exceeded that obtained with mineral fertilisers without manure by 255.4 g on the $N_{60}P_{120}K_{60}$ background and by 245.4 g on the $N_{90}P_{120}K_{60}$ background. The most vigorous and leafy plants were formed in 2019 (Fig. 5). However, in all years of this study, leaf mass exceeded stem mass. Thus, when $N_{60}P_{120}K_{60}$ was applied, leaf mass exceeded stem mass by 21.2 g in 2017, by 16.8 g in 2018 and by 18.4 g in 2019. When $N_{90}P_{120}K_{60}$ was applied, the corresponding differences were 62.7 g, 11.4 g and 90.7 g, respectively.

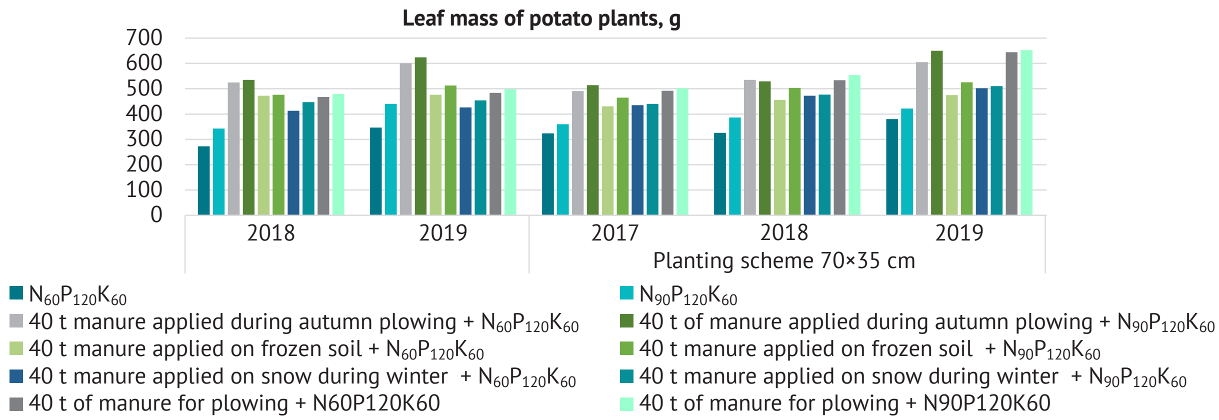

***Figure 5**. Leaf mass of potato plants depending on fertiliser application and planting density, g*
***Source:** compiled by the authors*

The same pattern was observed when manure was applied. Thus, when 40 t/ha of manure was applied during autumn ploughing on the $N_{60}P_{120}K_{60}$ background, leaf mass exceeded stem mass by 34.1 g in 2017, by 65.1 g in 2018 and by 17.2 g in 2019. On the $N_{90}P_{120}K_{60}$ background, the differences were 67.3 g, 66.4 g, and 29.0 g, respectively. The highest leaf mass per plant in 2019 was observed when manure was applied in spring before re-ploughing autumn-ploughed soil, with planting according to the 70×35 cm scheme. Thus, when 40 t/ha of manure was applied before spring re-ploughing on the $N_{60}P_{120}K_{60}$ background, leaf mass per plant reached 644.3 g, which was 264.4 g higher than without manure. On the $N_{90}P_{120}K_{60}$ background, the value was 652.5 g, which was 230.9 g higher. In the other manure treatments, leaf mass was also higher than in the treatment with $N_{60}P_{120}K_{60}$ without manure under the 70×25 cm planting scheme by 79.9-254.2 g, and on the $N_{90}P_{120}K_{60}$ background by 14.1-183.7 g.

The pattern of above-ground biomass formation depending on manure application timing and mineral fertiliser background is particularly clear when the three-year average data are analysed (Table 3).

***Table 3**. Effect of fertilisation and planting density on haulm formation per unit area, averaged over three years*

Planting scheme	Manure application dates	Weight of plant, g			Above-ground mass, t/ha		
		stems	leaves	total	stems	leaves	total
70×25 cm	$N_{60}P_{120}K_{60}$	277.5	296.3	573.8	15.84	16.91	32.75
	$N_{90}P_{120}K_{60}$	327.0	382.0	709.0	18.67	21.81	40.48
	40 t/ha manure applied during autumn ploughing + $N_{60}P_{120}K_{60}$	497.7	536.5	1,034.2	28.41	30.63	59.04
	40 t/ha manure applied during autumn ploughing + $N_{90}P_{120}K_{60}$	508.8	563.1	1,071.9	29.05	32.15	61.20
	40 t/ha manure applied on frozen soil + $N_{60}P_{120}K_{60}$	397.9	464.3	862.2	22.72	26.51	49.23
	40 t/ha manure applied on frozen soil + $N_{90}P_{120}K_{60}$	444.1	503.1	947.2	25.35	28.72	54.07
	40 t/ha manure applied on snow during winter + $N_{60}P_{120}K_{60}$	375.5	406.6	782.1	21.44	23.21	44.65
	40 t/ha manure applied on snow during winter + $N_{90}P_{120}K_{60}$	407.2	437.9	845.1	23.25	25.00	48.25
	40 t/ha manure applied before spring re-ploughing of autumn-ploughed soil + $N_{60}P_{120}K_{60}$	441.5	531.3	972.8	25.20	26.91	52.11
	40 t/ha manure applied before spring re-ploughing of autumn-ploughed soil + $N_{90}P_{120}K_{60}$	462.2	481.2	943.4	26.39	27.47	53.86

Table 3. Continued

Planting scheme	Manure application dates	Weight of plant, g			Above-ground mass, t/ha		
		stems	leaves	total	stems	leaves	total
70×35 cm70×35 cm	$N_{60}P_{120}K_{60}$	299.4	343.1	642.5	12.21	13.99	26.20
	$N_{90}P_{120}K_{60}$	341.6	389.4	731.0	13.93	15.88	29.81
	40 t/ha manure applied during autumn ploughing + $N_{60}P_{120}K_{60}$	511.7	543.5	1,055.2	20.87	22.17	43.04
	40 t/ha manure applied during autumn ploughing + $N_{90}P_{120}K_{60}$	599.6	631.1	1,230.7	24.46	25.74	50.20
	40 t/ha manure applied on frozen soil + $N_{60}P_{120}K_{60}$	438.7	453.7	892.4	17.89	18.51	36.40
	40 t/ha manure applied on frozen soil + $N_{90}P_{120}K_{60}$	459.5	498.0	957.5	18.74	20.31	39.05
	40 t/ha manure applied on snow during winter + $N_{60}P_{120}K_{60}$	443.8	470.0	913.08	18.10	19.17	37.27
	40 t/ha manure applied on snow during winter + $N_{90}P_{120}K_{60}$	452.4	475.8	928.2	18.45	19.41	37.86
	40 t/ha manure applied before spring re-ploughing of autumn-ploughed soil + $N_{60}P_{120}K_{60}$	503.7	556.7	1,060.4	20.55	22.71	43.26
	40 t/ha manure applied before spring re-ploughing of autumn-ploughed soil + $N_{90}P_{120}K_{60}$	523.2	569.2	1,092.4	21.34	23.22	44.56

Source: *compiled by the authors*

The table shows that, with a planting scheme of 70×25 cm, the lowest haulm weight per plant was observed when $N_{60}P_{120}K_{60}$ was applied; this was 135.2 g lower than when $N_{90}P_{120}K_{60}$ was applied. When 40 t/ha of manure was applied during autumn ploughing, haulm weight per plant increased by 460.4 g on the $N_{60}P_{120}K_{60}$ background and by 362.9 g on the $N_{90}P_{120}K_{60}$ background. When potatoes were planted according to the 70×35 cm scheme, haulm weight per plant increased under all fertiliser treatments. However, the highest haulm weight per plant was observed when 40 t/ha of manure was applied during autumn ploughing and in spring before re-ploughing autumn-ploughed soil. Thus, when manure was applied during autumn ploughing on the $N_{60}P_{120}K_{60}$ background, haulm weight exceeded that under denser planting by 21 g, and on the $N_{90}P_{120}K_{60}$ background by 158.8 g.

With spring application of manure before re-ploughing autumn-ploughed soil, haulm weight per plant increased compared with autumn application during autumn ploughing by 5.2 g on the $N_{60}P_{120}K_{60}$ background and by 138.3 g on the $N_{90}P_{120}K_{60}$ background. It should be noted that, although haulm weight per plant increased with wider spacing, total biomass per unit area decreased (Table 3). Thus, when $N_{90}P_{120}K_{60}$ was applied, the average total haulm weight over three years was 32.75 t/ha under the 70×25 cm planting scheme and 26.20 t/ha under the 70×35 cm scheme, which was 6.55 t/ha lower. When $N_{90}P_{120}K_{60}$ was applied, the corresponding values were 40.48 t/ha and 29.81 t/ha, respectively, with the wider planting scheme producing 10.67 t/ha less. The highest average haulm yield over three years (61.20 t/ha) was obtained when manure was applied during autumn ploughing with planting according to the 70×25 cm scheme. When the feeding area was expanded, haulm yield was 50.20 t/ha, or 11 t/ha lower. The same pattern was observed in the other experimental treatments.

DISCUSSION

Field studies by M.N. Suraganov *et al.* (2024) demonstrated that the number and weight of potato stems, with the number of stems per plant varying from 3-5 to 10-12, were correlated with tuber size. The larger the tuber, the larger the stems. The highest stem weight was 81.6-91.7 g in the treatments with the growth regulators Humika, Enrivel and Zerebra Agro, compared with 64.1 g in the control treatment. The lowest stem weight was observed following treatment with the growth regulator Gufos. In the research of D. Stewart *et al.* (1998), soil physical properties had a significant effect on potato yield, regardless of fertiliser application. The effect of changes in soil physical properties on plant growth was most evident when fertiliser was not applied. The results of D. Peddle *et al.* (2024) made it possible to determine the optimal leaf density and timing of measurements and also demonstrated the ability to detect vegetation stress and nitrogen deficiency in three potato varieties. These results will form the basis for further research using UAVs/drones/satellite systems and will be used to develop other methods for assessing plant physiology. In research by S. Nepal *et al.* (2016), the number of stems per plant was identified as an early predictor of potato yield and tuber size. For each treatment and location, the number of stems per plant, the number of tubers and average tuber size were compared. The physiological age of seed potatoes can influence the number of stems per plant, as well as the number and size of tubers available for harvest. Changes in harvested tuber size have economic consequences that depend on the market and pricing. Economic returns were analysed using the ordinary least squares method. The economic impact of physiological ageing of seed potatoes, expressed in dollars per hectare for the fresh and processing markets, was mixed.

N. Marks & P.S. Szecówka (2010) emphasised the beneficial effect of magnetic induction and radiation dose on stem length and number, leaf and stem weight, and the potato germination index. These treatments increased these parameters compared with the control treatment, demonstrating that magnetic stimulation of potato tubers has a beneficial effect on the vegetation of the above-ground parts of potato plants. The available data support the conclusions of the present study: increasing the nitrogen dose in the mineral fertiliser background from 60 to 90 kg/ha led to an increase in the number of stems by 0.1-0.4 stems per plant. The largest number of stems was recorded when manure was applied after spring re-ploughing of autumn-ploughed soil and potatoes were planted according to the 70×35 cm scheme (7.4 stems per plant), whereas the lowest number was recorded with mineral fertilisers alone 5.8 stems per plant).

The most important part of a potato plant is its leaves. A larger leaf area supports more active photosynthesis, which contributes to higher yield formation. M. Hossain *et al.* (1989) reported that, as the percentage of seed tubers infected with PLRV increased, growth parameters, including plant height and the number of stems per hill, as well as yield components, including the number and weight of tubers per hill and yield (t/ha), gradually declined. Similarly, N. Budanov *et al.* (2023) analysed biometric data and found that the largest number of leaves was observed in the 70×30 cm control treatment, whereas the smallest number was observed in the 70×20 cm treatment. These findings are consistent with the present study, in which the largest number of leaves was observed when manure was applied during ploughing and potatoes were planted according to the 70×35 cm scheme (210.4 leaves per plant). The lowest number was recorded when mineral fertilisers were applied at a rate of $N_{60}P_{120}K_{60}$ under the 70×35 cm planting scheme (153.1 leaves per plant). In addition, when the feeding area was expanded from 70×25 cm to 70×35 cm, the number of leaves increased by 9-12 leaves per plant. Therefore, the number of leaves and stems ultimately characterises the potential size of the harvest.

A. Zanon *et al.* (2013) determined the number of accumulated leaves on the main stem and the final leaf count. Variations in phyllochron, final leaf count and leaf area index were observed depending on the genotype in each growing season. It was found that the duration of the phases from seedling emergence to the onset of tuber formation and from the beginning of tuber formation to the onset of senescence determines tuber productivity. A. Jama-Rodzenska *et al.* (2021) reported that variety had a significant effect on potato tuber weight. Irrigation level had a significant effect only on total potato biomass, while the potato harvest date had a significant effect on both examined traits. The growth dynamics of the above-ground part and potato tubers were highest under constant irrigation level 1. Regardless of the variety studied, irrigation level 3 reduced potato biomass production. The highest water consumption was observed from the tuber growth period to flowering. These findings are also confirmed by the present study, in which manure application resulted in the formation of strong, well-developed stems. Expanding the feeding area from 70×25 cm to 70×35 cm contributed to an increase in haulm weight per plant. When manure was applied on frozen soil on the $N_{60}P_{120}K_{60}$ background, the increase was 47.1 g, and on the $N_{90}P_{120}K_{60}$ background, it was 8.4 g. When manure was applied on snow during winter, the increase was 117.0 g and 85.0 g, respectively. When manure was applied in spring before re-ploughing autumn-ploughed soil, the increase reached 49.5 g and 64.8 g, respectively. The largest increase in haulm weight per plant was observed when manure was applied before spring re-ploughing autumn-ploughed soil on the $N_{90}P_{120}K_{60}$ background, amounting to 114.1 g. The sharp increase in haulm weight when manure was applied during autumn ploughing and before spring re-ploughing can be explained by the higher nitrogen content in the soil, which stimulated rapid vegetative growth.

The results obtained are also consistent with the findings of X. Liu *et al.* (2025) and T.L. Gobena *et al.* (2022), who reported that balanced phosphorus nutrition improves potato growth, nutrient uptake and overall plant productivity. In the present study, the combined application of manure and mineral fertilisers contributed to more intensive vegetative development, confirming the importance of a balanced nutrient supply for the formation of a productive assimilation apparatus. Similar conclusions were reported by L. Adam *et al.* (2026), who demonstrated that planting density and nutrient management significantly influence tuber yield and plant development depending on environmental conditions. Furthermore, R. Setyobudi *et al.* (2024) emphasised that nutrient imbalance may negatively affect root development and delay phenological stages, whereas the balanced fertiliser systems used in the present experiment promoted more vigorous plant growth and biomass accumulation. Thus, the analysis shows that the results for the West Kazakhstan region are consistent with international and national studies on potato growth and development in terms of manure and mineral fertiliser application timing and planting density. At the same time, they reveal specific features associated with local climatic and soil conditions. The data confirm that the application of fertilisers at optimal rates and with an appropriate nutrient ratio makes it possible to regulate potato plant growth and development, thereby contributing to higher yield formation in the region.

CONCLUSIONS

The analysis of potato plant growth and development showed that these processes are influenced by mineral fertiliser rates, manure application timing, planting density and weather conditions. The mineral fertiliser rates and manure application timings studied in the experiment did not affect the timing of seedling emergence; however, they significantly influenced the onset and duration of interphase periods by up to 16 days. The growth and development of potato plants also depended on the meteorological conditions of the growing season. Manure application contributed to vigorous growth of the above-ground biomass of potato plants. As the feeding area expanded from 70×25 cm to 70×35 cm, haulm weight per plant also increased. The application of mineral fertilisers together with manure improved the soil supply of nitrogen, phosphorus and potassium and had a significant effect on plant growth and development. When manure was applied during autumn ploughing in combination with mineral fertilisers, the plants were 9.1-11.8 cm taller than in the treatments without manure.

Thus, manure application in all treatments increased the weight of above-ground biomass. The highest haulm weight was observed in the treatments where manure was applied during autumn ploughing and before spring re-ploughing of autumn-ploughed soil on the $N_{90}P_{120}K_{60}$ background. Prospects for further research include studying the long-term effects of combined organic and mineral fertilisation on potato yield and tuber quality, changes in soil microbiological activity and nutrient availability, and the adaptation of fertiliser application systems to different soil and climatic conditions. Further investigations should also focus on optimising planting density and irrigation regimes to improve resource-use efficiency and ensure sustainable potato production under changing climatic conditions.

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CONFLICT OF INTEREST

None.

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Вплив внесення гною з мінеральними добривами та густоти посадки на зростання та розвиток картоплі

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Анотація. Збільшення виробництва картоплі має здійснюватися не тільки за рахунок розширення площ під культурою, а головним чином – за рахунок підвищення врожайності. Для підвищення врожайності картоплі, поряд із застосуванням мінеральних добрив, велике значення має раціональне використання місцевих органічних добрив. Отже, метою даного дослідження було вивчення росту та розвитку рослин картоплі у залежності від термінів внесення гною у поєднанні з мінеральними добривами та густотою посадки. Польові дослідження здійснювалися систематичним методом з ярусним розташуванням варіантів у досвіді з 3-кратною повторністю. Найменша кількість стебел формувалася при внесенні $N_{60}P_{120}K_{60}$ (5,8 шт.) при посадці за схемою 70×25 см, а найбільше – при внесенні 40 т/га гною під зяб у поєднанні з мінеральними добривами в дозі $N_{90}P_{120}K_{60}$ (7 переорювання зябку та посадки за схемою 70х35 см (7,4 стебла) а також збільшується числа стебел у міру розширення площі живлення на 0,1-0,3 стебла. У середньому за 3 роки при весняному внесенні 40 гною на фоні $N_{60}P_{120}K_{60}$ кількість листя зросла на 50,6 шт., а на фоні $N_{90}P_{120}K_{60}$ – на 41,3 шт. Маса бадилля однієї рослини змінювалася при розширенні площі живлення, по роках і в залежності від термінів внесення гною, при розширенні площі харчування (70×35 см) маса бадилля одного куща зростає, де найбільша маса бадилля в середньому за 3 роки (61,20 т/га) була отримана при внесенні гною5 вона становила 50,20 т/га, чи 11 т менше. Така сама закономірність спостерігається і за іншими варіантами досвіду. За отриманими результатами польових дослідів у виробничих умовах будуть надані рекомендації виробництву, що дозволяють раціональніше використовувати органічні та мінеральні добрива та підвищувати продуктивність картоплі

Ключові слова: польові дослідження; підвищення врожайності; оранка; вага куща

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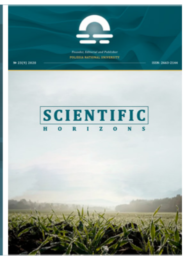

Assessment of the micronutrient status of arable land in Rivne region for the establishment of special raw material zones

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Abstract. Soil contamination by heavy metals and micronutrient deficiency in agricultural land reduce product quality and limit its suitability for infant and dietary nutrition, which necessitates a comprehensive study of micronutrient content in soils. The aim of the study was to assess the micronutrient status of arable land in Rivne region for the establishment of special raw material zones. The research was conducted on the basis of agrochemical monitoring data for 2015-2020 using correlation and regression

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analyses. It was established that in the Polissia zone the micronutrient content was as follows: manganese levels ranged from 4.6 to 17.1 mg/kg, copper from 0.1 to 0.75 mg/kg, cobalt from 0.18 to 2.57 mg/kg, and cadmium from 0.08 to 0.5 mg/kg; in the Forest-Steppe zone, manganese ranged from 10.08 to 21 mg/kg, copper from 0.08 to 0.23 mg/kg, cobalt from 0.24 to 0.42 mg/kg, and cadmium from 0.05 to 0.14 mg/kg. Correlation and regression analyses showed that the dynamics of changes in these elements exhibited significant fluctuations described by stochastic models with weak and strong correlation relationships. It was determined that most districts within the studied zones are unsuitable or only marginally suitable for the establishment of special raw material zones due to low copper and cadmium content; in the Forest-Steppe zone, nine districts were assessed as unsuitable. To ensure the production of raw materials suitable for infant and dietary nutrition, it is necessary to maintain high levels of manganese, copper, and cadmium availability. The obtained data make it possible to substantiate measures aimed at optimising soil micronutrient status and forming special raw material zones for the production of safe infant and dietary products

Keywords: soil quality; assessment of soil suitability; soil contamination; infant nutrition; product quality; raw material production

INTRODUCTION

The issue of establishing special raw material zones (SRMZs) in Ukraine stems from insufficient production volumes of raw materials for the manufacture of infant food products, which currently fail to satisfy even half of the existing demand. At the same time, due to the difficult socio-economic situation caused by the full-scale invasion of Ukraine by the Russian Federation in 2022, the process of granting SRMZ status to agricultural producers cultivating raw materials suitable for infant and dietary food production has slowed considerably. Addressing this issue should be facilitated through the implementation of strategic national priorities, in particular the organisational, social, and economic foundations of state policy in the field of providing children with adequate, high-quality, and safe nutrition in accordance with Law of Ukraine No. 142-V (2006). Equally important is compliance with the procedures for granting producers the status of SRMZs for the production of raw materials used in the manufacture of infant and dietary food products, in accordance with Resolution of the Cabinet of Ministers of Ukraine No. 1195 (2007).

An important aspect of ensuring the quality of such raw materials is their micronutrient composition, which directly influences the nutritional value of the products. The widespread deficiency of micronutrients in humans is attracting increasing attention from the international scientific community. One promising approach to addressing micronutrient deficiencies in food systems is the biofortification of crops (Mandial *et al.*, 2023). In particular, L. Galić *et al.* (2025) emphasised in their study that optimal human health depends on an adequate dietary intake of essential micronutrients, specifically selenium, zinc, copper, boron, manganese, molybdenum, iron, nickel and chlorine. At the same time, these elements play an important role in plant metabolic processes, and their deficiency is widespread in various agroecosystems around the world. There have been numerous cases where trace elements are found in soils at toxic concentrations, posing a risk to plant growth and human health. There is a need to understand the complex relationship between soil quality and human health, which occurs through the transfer of essential trace elements from the soil, as an abiotic environment, into the biotic systems of plants and animals that make up the human diet.

The increasing intensity of the dispersion of heavy metals and micronutrients in the environment and their involvement in the biogenic cycle has been documented both globally and in Ukraine. The spread of micronutrients in the environment is caused by both natural and anthropogenic factors. Natural causes include the weathering of rocks and minerals and soil erosion, while anthropogenic factors include human economic activities such as industrial emissions, the application of organic and mineral fertilisers to soils, and the widespread use of pesticides containing impurities of heavy metals and micronutrients. S. Razanov *et al.* (2022) also emphasised that the occurrence and accumulation of micronutrients in soils depend on the chemical forms in which they are present in parent materials or enter soils through atmospheric precipitation and dust, while the level of their toxicity within the "soil-plant-animal-human" system is determined by their content in both total and mobile forms. Similar conclusions were reported by (Emam & Soliman, 2022).

Despite the importance of ensuring adequate micronutrient availability in arable land for obtaining high yields and products of appropriate biological quality suitable for infant and dietary nutrition, the assessment of their content and spatial-temporal dynamics in the soils of Rivne region remains insufficiently studied. In this regard, the aim of the study was to assess the level of micronutrient availability in the arable lands of Rivne region for the subsequent establishment of SRMZs. To achieve this aim, the following objectives were set: (1) to evaluate the dynamics of changes in micronutrient content and the level of micronutrient availability in the arable lands of the Polissia and

Forest-Steppe zones of the region; (2) to determine the suitability of these lands, according to their micronutrient content, for the formation of SRMZs; (3) to substantiate the feasibility of measures aimed at restoring the optimal balance of micronutrients in arable soils.

LITERATURE REVIEW

Many scientists from other countries, including G. Ondrasek *et al.* (2025), emphasise that industrialisation, urbanisation, and intensive agriculture accelerate the global accumulation of heavy metals in soils. This is confirmed by the results of studies conducted in various countries around the world. Thus, the study by J. Qi *et al.* (2024) highlighted that industrial zones and chemical production in China increase the risk of soil contamination by heavy metals, among which cadmium poses the greatest threat due to its high concentration and ability to accumulate in plants, thereby negatively affecting soil quality and, consequently, human health. In the work of H. Binner *et al.* (2023), it was established that metals such as lead, zinc, chromium, and nickel exceed national safety limits in urban soils of Italy, Serbia, and the United Kingdom, thereby reducing water quality and posing a threat to human health. According to T.T.H. Truong *et al.* (2025), industrialisation and agricultural development in southern Vietnam contribute to increased concentrations of heavy metals in soils. High concentrations of anthropogenic arsenic, cadmium, manganese, lead, and zinc exceeding permissible limits were identified by A.M.A. Ahogle *et al.* (2023) in peri-urban agricultural soils of Nairobi, creating risks to public health. Similar trends in the accumulation of heavy metals in soils may be caused by various sources of input, particularly agrotechnogenic factors. For example, increases in their concentrations in Belgian soils by 1.7-5.3 times were observed during winter, which has been associated with manure application (Luo *et al.*, 2025).

Elevated concentrations of heavy metals in the human body are associated with metabolic disorders. In particular, the study by S. Cortés *et al.* (2021), conducted among the population of Chile, established that high concentrations of inorganic arsenic and nickel in blood are associated with elevated glucose levels and an increased risk of metabolic diseases. Research by R. Wu *et al.* (2024) indicated the significant role of chronic arsenic exposure in the development of gestational diabetes, while increased blood lead levels, as noted in the work of S. Heidari *et al.* (2022), result in reduced IQ in children under 12 years of age. V.A. Florez-Garcia *et al.* (2022) established that elevated cadmium levels are associated with an increased risk of breast cancer in women, while even low concentrations of mercury are capable of causing long-term adverse effects on the nervous, respiratory, and cardiovascular systems (Charkiewicz *et al.*, 2025). High serum copper levels are associated with an increased risk of stroke, myocardial infarction, and cardiovascular mortality (Muñoz-Bravo *et al.*, 2023). According to F.U. Haque *et al.* (2023), micronutrients such as copper, nickel, and zinc play a key role in crop production and food quality. It should also be noted that the minimum risk associated with human consumption of micronutrients through food products is achieved under conditions where the adequacy criterion, namely the boundary between deficiency and excess, is maintained.

At the same time, most studies provide insufficient coverage of the causes underlying both micronutrient deficiency and excess in the human body, particularly their relationship with soil properties. Manganese deficiency contributes to the development of diabetes and convulsive syndrome; zinc deficiency leads to congenital malformations in infants; a lack of molybdenum in the body results in intellectual disability; cobalt deficiency causes vitamin B12 deficiency and atrophy of the intestinal mucosa; while copper deficiency leads to disorders in the formation of the cardiovascular system, skeleton, and central nervous system, and aggravates hereditary diseases and cholesterol accumulation. Research by D. Jin *et al.* (2024) indicated that zinc deficiency is associated with a high prevalence of infectious diseases, whereas selenium deficiency may contribute to increased incidence of cardiovascular diseases among adults in the United States (Liang *et al.*, 2025). Since both deficiency and excess of micronutrients in the human body cause various pathological conditions, there is a need for their proper regulation within food chains, namely their content in soils, crop and livestock products, food products, dietary nutrition, and subsequent intake by humans, which is consistent with the concept of micronutrient transfer within the "soil-plant-human" system (Kabata-Pendias, 2004). This will contribute to the formation of a balanced micronutrient composition in the human body, which is a prerequisite for the sustainable functioning of its cells, tissues, organs, and systems, as well as for ensuring active longevity.

The content of micronutrients in soils is formed under the influence of a number of natural and anthropogenic factors. The content of mobile forms of micronutrients such as arsenic, chromium, copper, iron, magnesium, molybdenum, nickel, lead, strontium, and zinc is positively influenced by seasonal changes during winter-spring (wet seasons) compared with summer-autumn (dry seasons), whereas under drought conditions manganese, vanadium, and cadmium demonstrate increased extractability. Similar processes of mobilisation and transformation of micronutrients in soils are also largely regulated by soil properties, particularly the content of organic matter. According to the studies of S.S. Dhaliwal *et al.* (2019), organic matter determines the redistribution of zinc, copper, iron, manganese, boron, and molybdenum, since its accumulation promotes the transformation of adsorbed fractions into forms more available to plants.

Agrotechnical measures, particularly fertiliser application, play a significant role in the formation of micronutrient content in soils. It has been established, according to summarised data, that mineral fertilisers contain the following micronutrients: phosphorite meal contains manganese up to 1,800 mg/kg, zinc up to 1,000 mg/kg, copper up to 300 mg/kg, and cobalt up to 10 mg/kg. Simple superphosphate contains manganese up to 1,000 mg/kg, zinc up to 600 mg/kg, copper up to 270 mg/kg, and cobalt up to 10 mg/kg. Potassium sulphate contains manganese up to 13 mg/kg, zinc up to 8 mg/kg, copper up to 10 mg/kg, and cobalt up to 0.1 mg/kg. Calcium carbonate contains manganese up to 1,200 mg/kg, zinc up to 450 mg/kg, copper up to 125 mg/kg, and cobalt up to 0.4 mg/kg. Under conditions of irrational application of organic and mineral fertilisers to arable land and uncontrolled use of pesticides, contamination by heavy metals and micronutrients occurs (Römheld, 1991; Lisoval *et al.*, 2002). As a result, an imbalance of micronutrients available to plants is observed in arable soils due to certain elements occurring either in deficient states (low or very low availability) or in excessive states (high or very high availability).

MATERIALS AND METHODS

The methodological basis of the study consisted of a set of approaches and methods aimed at assessing the content and dynamics of micronutrients in soils. The study was conducted during 2020-2025 in Rivne region, Ukraine, within the Polissia and Forest-Steppe zones (GPS coordinates 50°59′ N, 26°24′ E). In the Polissia zone, sod-podzolic sandy loam soils and grey forest podzolised light loam soils predominate. The Forest-Steppe zone is characterised by typical chernozems and podzolised light loam chernozems, which are mainly used for cultivating cereal and industrial crops (winter wheat, soybean, maize, sunflower, rapeseed, barley, and oats). Soil samples for determining the content of manganese, copper, cobalt, and cadmium were collected using the "envelope" method at a distance of no less than 30 m from roads. The composite sample was formed from 20-25 point samples weighing 400-500 g. The sampling depth was no less than 20 cm.

The location of the composite sample collection was linked to cartographic reference objects using a GPS receiver and recorded in the field according to the coordinate system established by DSTU 4287:2004 (2004). The content of micronutrients in soil samples was determined by the atomic absorption method in accordance with DSTU 4770.6:2007 (2007), 4770.1:2007 (2007), 4770.5:2007 (2007), and 4770.3:2007 (2007) at the measurement laboratory for analytical support of agrochemical and agroecological research at the Rivne branch of the State Soil Protection Agency, which holds a certificate of conformity of the measurement system with the requirements of DSTU ISO 10012:2005 under No. 0117 dated 31 March 2013, issued by Testmetrstandart LLC. The selection of experimental data for 2015-2020 on micronutrient content in the soils of the region included weighted average indicators calculated from three replications, while the error values in determining micronutrient content in soils did not exceed those specified in the certificate, namely: manganese ≤21%, copper ≤9%, cobalt ≤7%, and cadmium ≤30%. The study also employed methods of retrospective analysis and comparison of data (2015-2020), generalisation (directions of changes in micronutrient content over time), analogy (investigation of similarities in the dynamics of changes in the content of individual micronutrients), and mathematical methods (correlation and regression analyses of micronutrient content dynamics using Microsoft Office Excel 2010), including determination of the correlation coefficient at the 5% significance level and testing of the null hypothesis H_0 when $F_{actual} > F_{theoretical}$.

The qualitative assessment of the obtained correlation coefficients was determined according to a scale ranging from 0 to 1: 0 – no relationship; 0.01-0.20 – very weak relationship; 0.21-0.50 – weak relationship; 0.51-0.70 – moderate relationship; 0.71-0.90 – strong relationship; and 0.91-1.0 – very strong relationship. The suitability of arable land for SRMZ requirements was determined according to the standard indicators of the content of mobile forms of micronutrients, namely: suitable – not lower than manganese 10.1 mg/kg, copper 0.21 mg/kg, cobalt 0.16 mg/kg, and cadmium 1.01 mg/kg; limited suitability – not lower than manganese 7.1 mg/kg, copper 0.16 mg/kg, cobalt 0.11 mg/kg, and cadmium 0.51 mg/kg; unsuitable – lower than manganese 7.0 mg/kg, copper 0.15 mg/kg, cobalt 0.1 mg/kg, and cadmium 0.5 mg/kg. The status of suitability for establishing SRMZs was assigned according to the micronutrient present at the minimum level. To assess the level of soil micronutrient availability, the standard grouping presented in Table 1 was used.

Table 1*. Levels of agricultural crop supply with mobile forms of micronutrients, mg/kg*

Micronutrient	Very low	Low	Medium	Elevated	High	Very high
Manganese	<5.1	5.1-7.0	7.1-10	10.1-15.0	15.1-20	>20
Copper	<0.11	0.11-0.15	0.16-0.20	0.21-0.30	0.31-0.5	>0.5
Cobalt	0.071	0.071-0.1	0.11-0.15	0.16-0.20	0.21-0.3	>0.3
Cadmium	0.1-0.2	0.21-0.50	0.51-1.0	1.01-1.50	1.51-2.0	>2.0

Note: *the extractant solution was an ammonium acetate buffer solution with pH = 4.8*
Source: *developed by the authors*

The indicated approaches and assessment criteria were used to analyse the micronutrient availability of arable land and to determine its suitability for the establishment of special raw material zones.

RESULTS AND DISCUSSION

Analysis of soil survey data from the arable lands of Rivne region showed that the soil cover of the districts within the Polissia zone is predominantly represented by sod-podzolic, gleyed, in some areas drained, sandy loam, meadow, and less frequently meadow-bog soil types. The Forest-Steppe zone is represented by grey forest podzolised light loam soils, typical chernozems, and podzolised light loam chernozems. According to agrochemical monitoring, the content of mobile forms of micronutrients in the soils of the districts within the Polissia zone during 2015-2020 varied within the following ranges: manganese from 4.6 to 17.1 mg/kg; copper from 0.1 to 0.75 mg/kg; cobalt from 0.18 to 2.57 mg/kg; and cadmium from 0.08 to 0.5 mg/kg (Table 2).

***Table 2**. Content of mobile forms of micronutrients in the soils of the Polissia zone, mg/kg*

District	Element	2015	2016	2017	2018	2019	2020
Berezne	Mn	9.23	14.6	14.9	12.9	12.75	12.7
	Cu	0.18	0.19	0.22	0.17	0.15	0.17
	Co	0.41	0.42	0.48	0.35	0.38	0.35
	Cd	0.12	0.12	0.11	0.12	0.11	0.11
Volodymyrets	Mn	4.60	6.70	7.90	6.40	6.24	6.30
	Cu	0.22	0.23	0.25	0.23	0.26	0.26
	Co	0.41	0.40	0.38	0.40	0.36	0.30
	Cd	0.10	0.10	0.11	0.12	0.09	0.10
Dubrovytsia	Mn	6.83	15.2	15.8	14.68	15.0	15.1
	Cu	0.11	0.10	0.12	0.11	0.12	0.12
	Co	0.22	0.20	0.24	0.22	0.25	0.31
	Cd	0.07	0.08	0.08	0.08	0.08	0.08
Zarichne	Mn	12.0	10.1	13.4	12.5	12.0	12.0
	Cu	0.17	0.12	0.18	0.12	0.12	0.12
	Co	0.41	0.44	0.45	0.42	0.41	0.41
	Cd	0.12	0.27	0.28	0.25	0.20	0.18
Kostopil	Mn	15.3	18.3	18.0	17.2	16.9	17.1
	Cu	0.88	0.87	0.81	0.85	0.80	0.75
	Co	2.56	2.54	2.60	2.57	2.61	2.57
	Cd	0.55	0.54	0.49	0.53	0.55	0.50
Rokytne	Mn	10.48	14.6	16.0	14.0	14.0	14.0
	Cu	0.10	0.11	0.12	0.11	0.10	0.10
	Co	0.32	0.31	0.33	0.32	0.31	0.31
	Cd	0.11	0.12	0.12	0.11	0.10	0.10
Sarny	Mn	6.93	10.4	11.08	9.47	10.0	10.12
	Cu	0.15	0.17	0.19	0.16	0.17	0.18
	Co	0.20	0.20	0.24	0.21	0.21	0.18
	Cd	0.11	0.11	0.10	0.11	0.12	0.11

***Source:** compiled by the authors*

The ranges of variation in the content of mobile forms of micronutrients in the Forest-Steppe zone were as follows: manganese from 10.08 to 23.5 mg/kg; copper from 0.08 to 0.23 mg/kg; cobalt from 0.24 to 0.42 mg/kg; and cadmium from 0.05 to 0.14 mg/kg. The micronutrient content by district is presented in Table 3.

***Table 3**. Content of mobile forms of micronutrients in the soils of the Forest-Steppe zone, mg/kg*

District	Element	2015	2016	2017	2018	2019	2020
Hoshcha	Mn	16.2	18.6	19.0	15.83	15.41	15.46
	Cu	0.12	0.12	0.15	0.13	0.11	0.13
	Co	0.35	0.36	0.32	0.34	0.34	0.35
	Cd	0.05	0.07	0.08	0.07	0.05	0.06
Demydivka	Mn	18.3	19.0	21.1	19.63	20.03	20.2
	Cu	0.24	0.19	0.21	0.21	0.19	0.18
	Co	0.33	0.32	0.29	0.31	0.35	0.36
	Cd	0.09	0.09	0.09	0.08	0.09	0.09

Table 3. Continued

District	Element	2015	2016	2017	2018	2019	2020
Dubno	Mn	12.21	13.45	14.01	13.5	13.21	13.4
	Cu	0.11	0.09	0.09	0.10	0.10	0.08
	Co	0.23	0.29	0.31	0.28	0.30	0.34
	Cd	0.12	0.12	0.12	0.11	0.11	0.11
Zdolbuniv	Mn	10.08	12.3	12.1	11.5	12.23	12.31
	Cu	0.1	0.14	0.16	0.13	0.15	0.14
	Co	0.33	0.37	0.23	0.31	0.27	0.30
	Cd	0.11	0.11	0.14	0.12	0.13	0.12
Korets	Mn	12.8	16.6	25.8	18.4	17.91	18.0
	Cu	0.18	0.18	0.28	0.21	0.19	0.20
	Co	0.31	0.36	0.29	0.32	0.34	0.31
	Cd	0.09	0.10	0.08	0.09	0.08	0.08
Mlyniv	Mn	16.9	16.8	16.3	17.65	18.02	17.9
	Cu	0.12	0.13	0.14	0.13	0.13	0.13
	Co	0.39	0.34	0.33	0.35	0.37	0.40
	Cd	0.09	0.10	0.11	0.10	0.11	0.12
Ostroh	Mn	12.6	11.2	19.69	14.5	15.1	15.0
	Cu	0.11	0.12	0.17	0.13	0.11	0.11
	Co	0.25	0.24	0.30	0.26	0.30	0.27
	Cd	0.11	0.10	0.10	0.10	0.10	0.10
Radyvyliv	Mn	12.4	15.8	16.3	15.9	15.31	15.2
	Cu	0.12	0.13	0.12	0.13	0.15	0.17
	Co	0.38	0.36	0.40	0.38	0.38	0.42
	Cd	0.12	0.12	0.12	0.14	0.15	0.14
Rivne	Mn	23.5	24.5	24.78	20.70	21.0	21.0
	Cu	0.16	0.21	0.19	0.19	0.21	0.23
	Co	0.46	0.44	0.41	0.44	0.40	0.42
	Cd	0.15	0.15	0.14	0.16	0.15	0.14

Source: *compiled by the authors*

Analysis of the dynamics of micronutrient content in the soils of the region demonstrates that during the observation period of 2015-2020 not only increases but also stabilisation or decreases in the investigated micronutrients occurred in soils (Tables 2, 3). According to D.R. Binde *et al.* (2025), the increase in the content of certain micronutrients and toxic elements in soils is caused by the intensification of agricultural land use, which serves as an important signal for long-term monitoring. Similar results regarding increases, stabilisation, and decreases in the content of individual elements in soils are demonstrated by Finnish monitoring studies reported by H. Soinne *et al.* (2022), as well as by the 25-year monitoring programme in Poland, where A. Wdowczyk *et al.* (2023) observed an increase in cadmium content in soils, while copper content remained relatively stable. Element losses in soils may be caused by filtration waters, whereas accumulation may occur through fertilisers or irrigation with wastewater, as demonstrated in the experiments of J. Wang *et al.* (2021), where increases in cadmium and lead content were recorded.

As shown in Tables 2 and 3, according to the content of mobile forms of micronutrients in the investigated soil types, the following descending sequence was formed: manganese > cobalt > copper > cadmium. Regarding micronutrients important for the nutrition of agricultural crops, manganese content varied from very low to very high availability, while cobalt content ranged from elevated to very high availability. The content of the moderately toxic micronutrient copper ranged from very low to very high availability, whereas the highly toxic cadmium ranged from very low to elevated availability.

As a result, an imbalance between the content of mobile forms of manganese, copper, cobalt, and cadmium is observed in the soils of the region at levels of very low, low, and very high availability, which, according to D. Hou *et al.* (2025), poses a threat to agricultural production and public health and requires regulation towards optimal values of elevated and high availability. The advisability of combining the analysis of micronutrients essential for plants with toxic elements was also noted by Q. Devalloir *et al.* (2023), who indicated that this approach provides a more comprehensive ecological picture; otherwise, conclusions may be oversimplified. Based on correlation and regression analyses, an assessment of the dynamics of changes in the content of mobile forms of micronutrients in the arable lands of the districts was carried out, the results of which are presented in Tables 4-7.

The table data demonstrate that the dynamics of micronutrient changes in the arable lands of most districts are described by stochastic models represented by increasing or decreasing linear trends with correlation coefficients ranging from very weak to strong relationships. Thus, in the arable lands of the districts of the Polissia zone, manganese content increased continuously during 2015-2020, most sharply in Dubrovytsia district and, conversely, more slowly in Kostopil district. According to the strength of the identified relationships, the arable lands of the Polissia zone in terms of annual manganese dynamics were assessed as follows: one district – 0.20, very weak relationship; five districts – 0.24-0.49, weak relationship; and one district – 0.62, moderate relationship. In the arable lands of the Forest-Steppe zone, manganese content changed inconsistently. In the soils of Hoshcha and Rivne districts, manganese content decreased during 2015-2020, whereas in the other seven districts it increased. According to the strength of the identified relationships, the arable lands of the Forest-Steppe zone in terms of manganese dynamics were assessed as follows: four districts – 0.28-0.46, weak relationship; three districts – 0.54-0.63, moderate relationship; and two districts – 0.76-0.77, strong relationship (Table 4).

***Table 4**. Relationships of changes in mobile forms of manganese in the arable lands of Rivne region, 2015-2020*

District	Equation	Correlation coefficient
	Polissia zone	
Berezne	$Y_1 = -552.0533 + 0.28x$	0.266
Volodymyrets	$Y_2 = -317.5962 + 0.1606x$	0.280
Dubrovytsia	$Y_3 = -2270.6181 + 1.1323x$	0.620
Zarichne	$Y_4 = -264.6857 + 0.1371x$	0.240
Kostopil	$Y_5 = -213.4381 + 0.1143x$	0.200
Rokytne	$Y_6 = -781.6248 + 0.3943x$	0.400
Sarny	$Y_7 = -747.7605 + 0.3754x$	0.490
	Forest-Steppe zone	
Hoshcha	$Y_8 = 964.3986 - 0.4697x$	-0.540
Demydivka	$Y_9 = -621.2786 + 0.3177x$	0.600
Dubno	$Y_{10} = -258.7776 + 0.1349x$	0.420
Zdolbuniv	$Y_{11} = -584.2738 + 0.2954x$	0.630
Korets	$Y_{12} = -1280.4419 + 0.6437x$	0.280
Mlyniv	$Y_{13} = -559.7433 + 0.286x$	0.770
Ostroh	$Y_{14} = -1052.2876 + 0.5289x$	0.340
Radyvyliv	$Y_{15} = -684.0562 + 0.3466x$	0.460
Rivne	$Y_{16} = 1583.5486 - 0.7737x$	-0.760

***Note:** Y – content of mobile forms of manganese, mg/kg; X – year of calculation (forecast)*
***Source:** developed by the authors*

According to the results of the regression analysis of changes in the dynamics of the content of mobile forms of manganese in the soils of the districts, linear equations were obtained with regression coefficients ranging from +0.1143 to +0.3943 in the Polissia zone and from +0.1349 to +0.6437 and from -0.4697 to -0.7737 in the Forest-Steppe zone. The obtained regression coefficients indicate a gradual increase in manganese content in the soils of the Polissia zone, whereas in the soils of the Forest-Steppe zone a more substantial increase in this micronutrient occurred in seven districts, while in two districts, conversely, its content decreased. The content of mobile forms of copper during 2015-2020 in the arable lands of Berezne, Zarichne, Kostopil, and Rokytne districts of the Polissia zone decreased, whereas in the other three districts it increased, most significantly in Volodymyrets district from 0.22 to 0.26 mg/kg. According to the strength of the identified relationships, the annual dynamics of copper in the arable lands of the Polissia zone were assessed as follows: three districts – 0.26-0.50, weak relationship; two districts – 0.58 and 0.65, moderate relationship; and two districts – 0.84 and 0.89, strong relationship. In the arable lands of the Forest-Steppe zone, copper content also changed inconsistently. Thus, in the arable lands of Hoshcha, Demydivka, Dubno, and Ostroh districts, copper content decreased, whereas in the other five districts it gradually increased. According to the strength of the identified relationships, the arable lands of the Forest-Steppe zone in terms of annual copper dynamics were assessed as follows: two districts – 0.08 and 0.16, very weak relationship; two districts – 0.30 and 0.34, weak relationship; two districts – 0.52 and 0.56, moderate relationship; and three districts – 0.74-0.87, strong relationship (Table 5).

Table 5. Relationships of changes in mobile forms of copper in the arable lands of Rivne region, 2015-2020

District	Equation	Correlation coefficient
	Polissia zone	
Berezne	$Y_1 = 12.8614\text{-}0.0063x$	-0.500
Volodymyrets	$Y_2 = -15.3219+0.0077x$	0.840
Dubrovytsia	$Y_3 = -5.651+0.0029x$	0.650
Zarichne	$Y_4 = 18.1225\text{-}0.0089x$	-0.580
Kostopil	$Y_5 = 48.0938\text{-}0.0234x$	-0.890
Rokytne	$Y_6 = 2.4124\text{-}0.0011x$	-0.260
Sarny	$Y_7 = -6.7471+0.0034x$	0.450
	Forest-Steppe zone	
Hoshcha	$Y_8 = 4.1502\text{-}0.00199x$	-0.30
Demydivka	$Y_9 = 17.4962\text{-}0.00857x$	-0.740
Dubno	$Y_{10} = 6.4357\text{-}0.0031x$	-0.420
Zdolbuniv	$Y_{11} = -11.3919+0.0057x$	0.520
Korets	$Y_{12} = -3.2519+0.0017x$	0.080
Mlyniv	$Y_{13} = -2.1757+0.0011x$	0.340
Ostroh	$Y_{14} = 4.16\text{-}0.0020x$	-0.160
Radyvyliv	$Y_{15} = -18.309+0.0091x$	0.870
Rivne	$Y_{16} = -19.9767+0.0100x$	0.780

Note: *Y – content of mobile forms of copper (mg/kg), X – year of calculation (forecast)*
Source: *developed by the authors*

According to the results of the regression analysis of changes in the dynamics of the content of mobile forms of copper in the soils of the districts, linear equations were obtained with regression coefficients indicating an increase in this micronutrient from +0.0029 to +0.0077 in three districts and a decrease from -0.0011 to -0.0089 in four districts of the Polissia zone. In the districts of the Forest-Steppe zone, the obtained linear equations had regression coefficients indicating an increase in copper content from +0.0011 to +0.01 in five districts and a decrease from -0.00199 to -0.00857 in four districts. The content of mobile forms of cobalt during 2015-2020 in the arable lands of Kostopil and Dubrovytsia districts of the Polissia zone increased, whereas in the other five districts it decreased. According to the strength of the identified relationships, the annual dynamics of cobalt in the arable lands of the districts of the Polissia zone were assessed as follows: four districts – 0.27-0.48, weak relationship; one district – 0.59, moderate relationship; and two districts – 0.80-0.85, strong relationship. In the arable lands of the Forest-Steppe zone, cobalt content changed as follows: in four districts it decreased over the years, whereas in the other five districts it increased, most significantly in Dubno district up to 0.34 mg/kg. According to the strength of the identified relationships, the arable lands of the Forest-Steppe zone in terms of annual cobalt dynamics were assessed as follows: two districts – 0.06-0.16, very weak relationship; two districts – 0.30-0.41, weak relationship; four districts – 0.51-0.70, moderate relationship; and one district – 0.80, strong relationship (Table 6).

Table 6. Relationships of changes in mobile forms of cobalt in the arable lands of Rivne region, 2015-2020

District	Equation	Correlation coefficient
	Polissia zone	
Berezne	$Y_1 = 32.1019 - 0.0157x$	-0.590
Volodymyrets	$Y_2 = 37.8429 - 0.0186x$	-0.850
Dubrovytsia	$Y_3 = -33.1929 + 0.0166x$	0.800
Zarichne	$Y_4 = 7.3405 - 0.0034x$	-0.370
Kostopil	$Y_5 = -10.6829 + 0.0066x$	0.480
Rokytne	$Y_6 = 3.7752 - 0.0017x$	-0.39
Sarny	$Y_7 = 5.971 - 0.0029x$	-0.270
	Forest-Steppe zone	
Hoshcha	$Y_8 = 2.649 - 0.0011x$	-0.16
Demydivka	$Y_9 = 14.6605 + 0.0074x$	0.540
Dubno	$Y_{10} = -31.4119 + 0.0157x$	0.800
Zdolbuniv	$Y_{11} = 21.6295 - 0.0106x$	-0.410
Korets	$Y_{12} = 2.051 - 0.0009x$	-0.060
Mlyniv	$Y_{13} = -8.8595 + 0.0046x$	0.300

Table 6. Continued

District	Equation	Correlation coefficient
Ostroh	$Y_{14} = -13.5643 + 0.0069x$	0.510
Radyvyliv	$Y_{15} = -13.4476 + 0.0069x$	0.620
Rivne	$Y_{16} = 17.1448 - 0.0083x$	-0.700

Source: *compiled by the authors*

According to the results of the regression analysis of changes in the dynamics of the content of mobile forms of cobalt in the soils of the districts, linear equations were obtained with regression coefficients indicating an increase in this micronutrient from +0.0066 to +0.0166 in two districts and a decrease from -0.0017 to -0.0186 in five districts of the Polissia zone. In the districts of the Forest-Steppe zone, the obtained linear equations had regression coefficients indicating an increase in cobalt content in soils from +0.0046 to +0.0157 in five districts and a decrease from -0.0009 to -0.0106 in four districts. The content of mobile forms of cadmium during 2015-2020 in the arable lands of the Polissia zone increased noticeably in three districts, namely Dubrovytsia, Zarichne, and Sarny districts, whereas in the other four districts it gradually decreased. According to the strength of the identified relationships, the annual dynamics of cadmium in the arable lands of the Polissia zone were assessed as follows: two districts – 0.05-0.10, very weak relationship; two districts – 0.34-0.37, weak relationship; two districts – 0.65-0.68, moderate relationship; and one district – 0.72, strong relationship. In the arable lands of the Forest-Steppe zone, cadmium content decreased in seven districts to values of 0.06 mg/kg, whereas in two districts it increased to values of 0.14 mg/kg. According to the strength of the identified relationships, the annual dynamics of cadmium in the arable lands of the Forest-Steppe zone were assessed as follows: two districts – 0.09-0.13, very weak relationship; two districts – 0.21-0.41, weak relationship; two districts – 0.65-0.65, moderate relationship; and three districts – 0.84-0.88, strong relationship (Table 7).

Table 7*. Relationships of changes in mobile forms of cadmium in the arable lands of Rivne region, 2015-2020*

District	Equation	Correlation coefficient
	Polissia zone	
Berezne	Y_1=4.15-0.002x	-0.680
Volodymyrets	Y_2=1.2562-0.0006x	-0.100
Dubrovytsia	Y_3=-2.8038+0.0014x	0.650
Zarichne	Y_4=-3.2419+0.0017x	0.050
Kostopil	Y_5=10.9024-0.0051x	-0.370
Rokytne	Y_6=7.0271-0.0034x	-0.72
Sarny	Y_7=-2.1957+0.0011x	0.340
	Forest-Steppe zone	
Hoshcha	Y_8=1.2162-0.0006x	-0.090
Demydivka	Y_9=0.6648-0.0003x	-0.130
Dubno	Y_{10}=5.3029-0.0026x	-0.880
Zdolbuniv	Y_{11}=5.0662-0.00245x	-0.410
Korets	Y_{12}=5.851-0.0029x	-0.650
Mlyniv	Y_{13}=-9.6943+0.0049x	0.870
Ostroh	Y_{14}=2.9838-0.0014x	-0.650
Radyvyliv	Y_{15}=-11.9733+0.006x	0.840
Rivne	Y_{16}=1.8776-0.0009x	-0.210

Note: *Y – content of mobile forms of cadmium, mg/kg; X – year of calculation (forecast)*
Source: *compiled by the authors*

According to the results of the regression analysis of changes in the dynamics of the content of mobile forms of cadmium in the soils of the districts, linear equations were obtained with regression coefficients indicating an increase in this micronutrient from +0.0011 to +0.0017 in three districts and a decrease from -0.0006 to -0.0051 in four districts of the Polissia zone. In the districts of the Forest-Steppe zone, the obtained linear equations had regression coefficients indicating an increase in cadmium content in soils from +0.0049 to +0.006 in two districts, whereas in seven districts it decreased from -0.0003 to -0.0029. At the same time, it should be noted that according to forecast calculations for 2025, manganese content in the arable lands of the region is characterised by accumulation levels that meet the requirements for the establishment of SRMZs for the cultivation of products intended for infant and dietary nutrition. In the soils of the Polissia zone, six out of seven districts correspond to the categories of elevated, high, and very high availability; accordingly, these lands are assessed as suitable for the establishment of such zones, whereas the lands of Volodymyrets district, with medium manganese content, belong to the category of limited suitability (Table 8).

***Table 8**. Assessment of the suitability of arable lands in the Polissia zone for the establishment of special raw material zones*

District	Element	2015	2020	2025	Micronutrient availability	Suitability for the establishment of SRMZs
Berezne	Mn	9.23	12.7	14.95	elevated	suitable
	Cu	0.18	0.17	0.10	very low	unsuitable
	Co	0.41	0.35	0.31	very high	suitable
	Cd	0.12	0.11	0.10	very low	unsuitable
Volodymyrets	Mn	4.60	6.30	7.62	medium	limited suitability
	Cu	0.22	0.26	0.27	elevated	suitable
	Co	0.41	0.30	0.18	elevated	suitable
	Cd	0.10	0.10	0.041	very low	unsuitable
Dubrovytsia	Mn	6.83	15.1	22.29	very high	suitable
	Cu	0.11	0.12	0.22	elevated	suitable
	Co	0.22	0.31	0.42	very high	suitable
	Cd	0.07	0.08	0.031	very low	unsuitable
Zarichne	Mn	12.0	12.0	12.94	elevated	suitable
	Cu	0.17	0.12	0.10	very low	unsuitable
	Co	0.41	0.41	0.46	very high	suitable
	Cd	0.12	0.18	0.20	very low	unsuitable
Kostopil	Mn	15.3	17.1	18.02	high	suitable
	Cu	0.88	0.75	0.71	very high	suitable
	Co	2.56	2.57	2.68	very high	suitable
	Cd	0.55	0.50	0.58	medium	limited suitability
Rokytne	Mn	10.48	14.0	16.83	high	suitable
	Cu	0.10	0.1	0.18	medium	limited suitability
	Co	0.32	0.31	0.33	very high	suitable
	Cd	0.11	0.10	0.14	very low	unsuitable
Sarny	Mn	6.93	10.1	12.42	elevated	suitable
	Cu	0.15	0.18	0.14	low	unsuitable
	Co	0.20	0.18	0.10	medium	limited suitability
	Cd	0.11	0.11	0.032	very low	unsuitable

***Source:** compiled by the authors*

According to the content of mobile forms of manganese, the arable lands of the Forest-Steppe zone belong to the categories of elevated, high, and very high availability, which provides grounds for assessing them as suitable for the establishment of special raw material zones (Table 9). According to the forecast up to 2025 regarding copper content, the arable lands of the Polissia zone are characterised predominantly by elevated and very high availability (three districts). At the same time, Rokytne district, with medium copper content, belongs to the category of limited suitability, whereas Berezne, Zarichne, and Sarny districts, with very low and low content, are classified as unsuitable (Table 8). In the Forest-Steppe zone, according to the content of mobile forms of copper, Rivne district corresponds to the category of elevated availability and is suitable for the establishment of raw material zones. Dubno and Korets districts belong to the category of medium availability and are assessed as having limited suitability. The lands of the other six districts, characterised by very low and low copper content, were classified as unsuitable (Table 9).

***Table 9**. Assessment of the suitability of arable lands in the Forest-Steppe zone for the establishment of special raw material zones*

District	Element	2015	2020	2025	Micronutrient availability	Suitability for the establishment of SRMZs
Hoshcha	Mn	16.2	15.46	13.28	elevated	suitable
	Cu	0.12	0.13	0.12	low	unsuitable
	Co	0.35	0.35	0.42	very high	suitable
	Cd	0.05	0.06	0.001	very low	unsuitable

Table 9. Continued

District	Element	2015	2020	2025	Micronutrient availability	Suitability for the establishment of SRMZs
Demydivka	Mn	18.3	20.2	22.06	very high	suitable
	Cu	0.24	0.18	0.14	low	unsuitable
	Co	0.33	0.36	0.32	very high	suitable
	Cd	0.09	0.09	0.06	very low	unsuitable
Dubno	Mn	12.21	13.4	14.40	elevated	suitable
	Cu	0.11	0.08	0.16	medium	limited suitability
	Co	0.23	0.34	0.38	very high	suitable
	Cd	0.12	0.11	0.04	very low	unsuitable
Zdolbuniv	Mn	10.08	12.31	13.91	elevated	suitable
	Cu	0.1	0.14	0.15	low	unsuitable
	Co	0.33	0.30	0.16	elevated	suitable
	Cd	0.11	0.12	0.10	very low	unsuitable
Korets	Mn	12.8	18.0	23.05	very high	suitable
	Cu	0.18	0.20	0.19	medium	limited suitability
	Co	0.31	0.31	0.23	high	unsuitable
	Cd	0.09	0.08	0.02	very low	unsuitable
Mlyniv	Mn	16.9	17.9	19.41	high	suitable
	Cu	0.12	0.13	0.05	very low	unsuitable
	Co	0.39	0.40	0.46	very high	suitable
	Cd	0.09	0.12	0.23	low	unsuitable
Ostroh	Mn	12.6	15.0	18.73	high	suitable
	Cu	0.11	0.11	0.11	low	unsuitable
	Co	0.25	0.27	0.41	very high	suitable
	Cd	0.11	0.10	0.15	very low	unsuitable
Radyvyliv	Mn	12.4	15.2	17.81	high	suitable
	Cu	0.12	0.17	0.12	low	unsuitable
	Co	0.38	0.42	0.52	very high	suitable
	Cd	0.12	0.14	0.18	very low	unsuitable
Rivne	Mn	23.5	21.0	16.81	high	suitable
	Cu	0.16	0.23	0.27	elevated	suitable
	Co	0.46	0.42	0.34	very high	suitable
	Cd	0.15	0.14	0.06	very low	unsuitable

Source: *compiled by the authors*

According to forecast calculations up to 2025 regarding cobalt content, the arable lands of the Polissia zone are predominantly characterised by elevated and very high availability (six districts), which provides grounds for classifying them as suitable for the establishment of special raw material zones. At the same time, in Sarny district, where a medium level of availability was recorded, the lands are assessed as having limited suitability (Table 8). In the Forest-Steppe zone, according to the content of mobile forms of cobalt, eight districts belong to the categories of elevated and very high availability, indicating the feasibility of establishing special raw material zones on these lands. The lands of Korets district, characterised by a very low cobalt content, were classified as unsuitable (Table 9). According to forecast calculations up to 2025 regarding cadmium content, the arable lands of the Polissia zone are predominantly characterised by a very low level of availability (six districts) and belong to the category unsuitable for the establishment of SRMZs. Only in Kostopil District was a medium level of availability recorded, corresponding to the status of lands with limited suitability (Table 8). In the Forest-Steppe zone, the arable lands of all nine districts, according to the content of mobile forms of cadmium, belong to the categories of low and very low availability and were therefore classified as unsuitable for the establishment of special raw material zones (Table 9).

According to the availability of the four micronutrients, the arable lands of the Polissia zone were assessed up to 2025 as follows. In Kostopil district, where medium cadmium content, high manganese content, and very high copper and cobalt content were recorded, the lands were classified as having limited suitability for the establishment of SRMZs. In Dubrovytsia, Rokytne, and Volodymyrets districts, the lands were unsuitable due to the very low cadmium content. In Berezne, Zarichne, and Sarny districts, the lands also belonged to the category of unsuitable because of the very low and low contents of copper and cadmium.

According to the forecast up to 2025, the arable lands of the Forest-Steppe zone are assessed as unsuitable for the establishment of SRMZs. In Rivne district, this is due to the very low cadmium content, whereas in the other eight districts it is caused by the low and very low content of mobile forms of copper and cadmium. In order to transfer the arable lands of the region into the category suitable for the establishment of SRMZs and to obtain high-quality raw materials for the production of infant and dietary food products under conditions of very low copper and cadmium content in sod-podzolic, grey forest, and podzolised chernozem soils, the application of modern biotechnologies is considered appropriate. In particular, according to M. Tavan *et al.* (2024), such approaches involve the use of traditional plant breeding and agronomic practices aimed at increasing micronutrient content to elevated and high levels of soil availability through the application of organic and mineral fertilisers (manure, superphosphate containing cadmium, and double superphosphate containing copper). This analysis of micronutrient dynamics reveals the presence of certain limitations that may be addressed in further research and publications. In particular, this concerns the study of the dynamics of heavy metals such as nickel, lead, molybdenum, and arsenic in different soil types of the region, the excess of which in organisms may produce toxic effects and influence the classification of these soils as unsuitable for the establishment of SRMZs. The absence of such data indicates the limitations of the present study and points to directions for further investigation.

CONCLUSIONS

For the first time, it was established that the dynamics of changes in the content of mobile forms of micronutrients in the arable lands of the region are described by stochastic models of the following types: for manganese, increasing linear trends were identified in all seven districts of the Polissia zone, while in the Forest-Steppe zone increasing linear trends were identified in seven districts and decreasing linear trends in two districts. For copper, increasing linear trends were identified in three districts of the Polissia zone, whereas decreasing linear trends were identified in four districts; in the Forest-Steppe zone, the content remained unchanged or followed increasing linear trends in five districts, while decreasing linear trends were observed in four districts. For cobalt, increasing linear trends were identified in two districts of the Polissia zone and decreasing linear trends in the remaining five districts; in the Forest-Steppe zone, increasing linear trends were observed in five districts and decreasing linear trends in the remaining four districts. For cadmium, increasing linear trends were observed in three districts of the Polissia zone and decreasing linear trends in four districts, whereas in the Forest-Steppe zone increasing linear trends were identified in two districts and decreasing linear trends in the remaining seven districts.

According to the indicators of mobile forms of micronutrient availability, the arable lands of the region, based on the forecast up to 2025, were assessed for the establishment of SRMZs as follows: in Kostopil District of the Polissia zone, with a limiting medium cadmium content, the lands were classified as having limited suitability; in Volodymyrets, Dubrovytsia, and Rokytne districts, with limiting very low cadmium content, and in three other districts of this zone, with low and very low copper and cadmium content, the lands were classified as unsuitable. In Rivne District of the Forest-Steppe zone, with limiting very low cadmium content, and in the other eight districts of this zone, with low and very low copper and cadmium content, the lands were classified as unsuitable. The sod-podzolic, grey forest, typical chernozem, and podzolised chernozem soils of the region, since the content of mobile forms of manganese, copper, cobalt, and cadmium does not exceed the maximum permissible levels, are suitable for obtaining environmentally safe agricultural products. However, for the production of raw materials suitable for the manufacture of infant and dietary food products, adjustment of the micronutrient content in these district soils is required in order to restore their optimal balance (at the level of elevated and high availability), namely: manganese from 15 to 20 mg/kg, copper from 0.31 to 0.5 mg/kg, cobalt from 0.16 to 0.30 mg/kg, and cadmium from 1.0 to 1.5 mg/kg.

Producers of raw materials cultivated on the arable lands of the region and used in the manufacture of infant and dietary food products are advised to maintain an optimal balance of mobile forms of micronutrients through the application of organic and mineral fertilisers containing micronutrients as impurities, namely phosphorite meal, simple superphosphate, 40% potassium salt, potassium sulphate, calcium carbonate, and manure. Prospects for further research include the refinement and validation of the proposed stochastic models describing the dynamics of mobile forms of micronutrients, the expansion of spatial analysis to other soil-climatic zones, and the assessment of the effectiveness of measures aimed at optimising their content while taking environmental risks and the impacts of climate change into account.

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CONFLICT OF INTEREST

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Оцінювання забезпеченості мікроелементами орних земель Рівненської області для створення спеціальних сировинних зон

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Анотація. Забруднення ґрунтів важкими металами та дефіцит мікроелементів у сільськогосподарських угіддях знижують якість продукції та обмежують можливість її використання для дитячого і дієтичного харчування, що зумовлює необхідність комплексного дослідження вмісту мікроелементів у ґрунтах. Метою дослідження було оцінювання забезпеченості мікроелементами орних земель Рівненської області для створення на них спеціальних сировинних зон. Дослідження було виконано на основі даних агрохімічного моніторингу за 2015-2020 роки з використанням кореляційного та регресійного аналізів. Встановлено, що у зоні Полісся вміст мікроелементів становив: рівень марганцю був – 4,6-17,1 мг/кг, міді – 0,1-0,75 мг/кг,, кобальту – 0,18-2,57 мг/кг,, кадмію – 0,08-0,5 мг/кг,; у зоні Лісостепу – марганцю 10,08-21 мг/кг,, міді 0,08-0,23 мг/кг,, кобальту 0,24-0,42 мг/кг,, кадмію 0,05-0,14 мг/кг,. Кореляційний та регресійний аналізи показали, що динаміка змін цих елементів мала значні коливання, що описуються стохастичними моделями зі слабкими та сильними кореляційними зв'язками. Встановлено, що більшість районів досліджуваних зон є непридатними або обмежено придатними для створення спеціальних сировинних зон через низький вміст міді та кадмію; у зоні Лісостепу дев'ять районів оцінюються як непридатні. Для забезпечення виробництва сировини, придатної для дитячого та дієтичного харчування, необхідно підтримувати високий рівень забезпеченості марганцем, міддю та кадмієм. Отримані дані дозволяють обґрунтувати заходи щодо оптимізації забезпеченості ґрунтів мікроелементами та формування спеціальних сировинних зон для виробництва безпечної дитячої та дієтичної продукції

Ключові слова: якість ґрунту; оцінка придатності ґрунтів; забруднення ґрунтів; дитяче харчування; якість продукції; виробництво сировини

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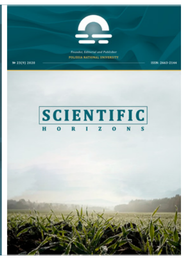

Patterns of ^{137}Cs accumulation in the fruiting bodies of mushrooms in moist relatively fertile forest sites of the Zhytomyr Polissia region

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Abstract. The aim of the study was to investigate the existing patterns of radioactive contamination in mushrooms growing under moist, relatively fertile forest site conditions. The investigation was carried out in Zhytomyr Polissia region within a widespread but poorly studied forest site type in terms of radioecology – moist relatively fertile forest site. The study elucidated the values of indicators characterising

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the intensity of ^{137}Cs accumulation in fresh and dry mushroom fruiting bodies, namely the ^{137}Cs concentration ratio and the aggregated transfer coefficient of ^{137}Cs. The high concentration ratios observed in dry samples connected with the substantial loss of moisture during drying. Significant interspecific differences in ^{137}Cs accumulation in mushroom fruiting bodies were identified, allowing the establish of a ranked series reflecting the intensity of radionuclide uptake by different species. Values of concentration ratio of radionuclide in fresh mushrooms varied from 0.01 ± 0.005 (*Lepista sordida*) to 7.4 ± 1.23 (*Paxillus involutus*). The excess of the maximum value of this index over the minimum reached 740 times. Values of concentration ratio of radionuclide in dry mushrooms varied from 0.15 ± 0.02 in *Hygrophorus eburneus* to 90.9 ± 16.54 in *Paxillus involutus*. In fresh fruiting bodies ranked series in descending order of concentration ratio can be build up: *Paxillus involutus* → *Imleria badia* → *Suillus luteus*, and in dry mushroom fruiting bodies – *Paxillus involutus* → *Suillus luteus* → *Imleria badia*. The results have practical significance for identifying forest areas which require radiological control of edible mushrooms during harvesting. The results can also be applied for organisation and implementation of radioecological monitoring programme in radioactively contaminated forest ecosystems

Keywords: type of forest site conditions; radionuclide; activity concentration; concentration ratio; aggregated transfer coefficient; drying coefficient

INTRODUCTION

High fungi (mushrooms) play an important role in the biogeochemical cycle of chemical elements in forest ecosystems, including radionuclides introduced as a result of anthropogenic nuclear accidents. This role – redistribution of radioactive elements within the soil and in the pathways and intensity of their transfer to various components of forest ecosystems. Moreover, the capacity of mushrooms to influence the radionuclide redistribution in forest ecosystems contributes to their accumulation within mushroom fruiting bodies. Since the fruiting bodies of many mushroom species are consumed by humans, this process can lead to the transfer of radionuclides into the human body.

Over time, the number of publications addressing radioactive contamination in edible mushrooms has not substantially increased. Most scientific works have focused on measuring radionuclides content in mushrooms during specific time periods, with results varying considerably among European countries. These differences are largely attributed to varying degrees of radioactive contamination across regions. For instance, German researchers investigated the ^{137}Cs content in two mushroom species – *Imleria badia* (Fr.) Vizzini and *Boletus edulis* Bull. – in the Bavarian Forest National Park, an area affected by fallout from the Chornobyl accident (Ernst *et al.*, 2022). Their results showed that the ^{137}Cs activity concentration in *Imleria badia* was significantly higher than in *Boletus edulis*. Based on these findings, the researchers recommended the consumption of *Boletus edulis* only, as approximately one-third of the tested *Imleria badia* samples exceeded the permissible levels of ^{137}Cs content. The elevated radionuclide levels in mushroom fruiting bodies were attributed to the high ^{137}Cs concentrations in soil layers rich in organic matter. Similar results have been observed when comparing the ^{137}Cs content in various species of *Tricholoma* spp. across different European countries between 1971-2016 (Falandysz *et al.*, 2022).

Similar results were obtained by J. Falandysz *et al.* (2019), who examined ^{137}Cs concentrations in fruiting bodies of *Cortinarius caperatus* (Pers.) Fr. across 22 locations in Northern Poland. Their findings also revealed high levels of radioactive contamination in mushroom fruiting bodies, leading the authors to recommend further studies on radioactive contamination of forest soils. A comparison of the radioactive contamination of *Boletus eduli* over time showed that contamination levels were lower during 1986-1994 than during 1995-2016. The researchers attributed this trend to the gradual downward migration of ^{137}Cs into deeper soil layers following their initial deposition. Similar conclusions were drawn by O. Ronda *et al.* (2022), who analysed seven wild mushroom species from different regions of the country – edible species (*Imleria badia*, *Cantharellus cibarius* Fr., *Xerocomus subtomentosus* (L.) Quél., and *Suillus luteus* (L.) Roussel) and inedible but animal-edible species (*Paxillus involutus* (Batsch) Fr., *Tylopilus felleus* (Bull.) P. Karst., and *Russula emetica* (Schaeff.) Pers.). Similar results have been obtained by I. Mirończuk-Chodakowska *et al.* (2025) and M. Gembal *et al.* (2026).

Following the Chornobyl accident, Ukrainian researchers periodically investigated the content of ^{137}Cs in the fruiting bodies of *Suillus luteus* both within the Chornobyl Exclusion Zone and in adjacent areas of the Kyiv region (Zarubina *et al.*, 2021). It was found that during the first 10-12 years after the radionuclides entered forest ecosystems, the activity concentration of ^{137}Cs in mushrooms increased, followed by a gradual decline that continues to the present day. Although the study included data from six research sites with different observation periods, the overall temporal trends in ^{137}Cs activity concentration in the fruiting bodies of *Suillus luteus* were consistent across all sites.

An analysis of the available literature allows several generalisations to be made. After the Chornobyl accident, systematic monitoring of radioactive contamination in mushrooms was not maintained in Ukraine or in other countries affected by radioactive fallout. This lack of consistency is largely due to the challenges of conducting long-term studies on permanent sample plots, since mushroom fruiting bodies do not appear regularly in the same locations. Furthermore, most previous investigations were limited to pure pine stands growing on poor or relatively poor soils (infertile and relatively infertile pine site types). Thus, the present study aimed to examine the current patterns of radioactive contamination of mushrooms under moist relatively fertile forest site conditions.

MATERIALS AND METHODS

The study was conducted on temporary sample plots located in the forests of the State Specialized Forest Enterprise "Forests of Ukraine", Branch "Stolychnyi Forest Office", Korostenske Forestry Management Unit, Luhynske Forestry, during August-September 2022-2023 (Fig. 1). The research was carried out in accordance with the general principles of sustainable forest management and biodiversity conservation as outlined in the Convention on Biological Diversity (1992). The preliminary selection of sampling sites was carried out in the office based on an analysis of forest management documentation. For field research, typical for the region forest stands in moist relatively fertile forest site conditions were selected. The selected stands had the following characteristics: Compartment 79, subcompartment 4, stand composition: alder (*Alnus glutinosa* (L.) Gaertn.) 50%, birch (*Betula pendula* Roth.) 20%, aspen (*Populus tremula* L.) 10%, pine (*Pinus sylvestris* L.) 10%, oak (*Quercus robur* L.) 10% + elm (*Ulmus glabra* Huds.), age – 49 years, stand quality class – II, forest type – moist relatively fertile hornbeam-oak-pine forest, relative density of stocking – 0.60, stock – 130 m^3·ha^{-1}; Compartment 79, subcompartment 6, stand composition: oak 90%, pine 10%, age – 130 years, stand quality class – II, forest type – moist relatively fertile hornbeam-oak-pine forest, relative density of stocking – 0.50, stock – 260 m^3·ha^{-1}; Compartment 79, subcompartment 8, stand composition: oak 70%, birch 20%, pine 10%, age – 65 years, stand quality class – II, forest type – moist relatively fertile hornbeam-oak-pine forest, relative density of stocking – 0.70, stock – 230 m^3·ha^{-1}; Compartment 85, subcompartment 34, stand composition: – oak 80%, pine 20% + aspen, age – 140 years, stand quality class – III, forest type – moist relatively fertile hornbeam-oak-pine forest, relative density of stocking – 0.40, stock – 200 m^3·ha^{-1}; Compartment 86, subcompartment 3, stand composition: – oak 50%, birch 30%, pine 20%, age – 64 years, stand quality class – II, forest type – moist relatively fertile hornbeam-oak-pine forest, relative density of stocking – 0.60, stock – 190 m^3·ha^{-1}; Compartment 86, subcompartment 14, stand composition: aspen 50%, oak 20%, birch 20%, pine 10%, age – 74 years, stand quality class – 2, forest type – moist relatively fertile hornbeam-oak-pine forest, relative density of stocking – 0.60, stock – 300 m^3·ha^{-1}.

Figure 1. *Map of mushroom fruiting body collection sites in moist relatively fertile forest (marked with white lines)*
Source: *created by the authors*

Samples of mushroom fruiting bodies were collected from each sample plot, with a minimum of three and a maximum of six samples per plot, depending on fruiting intensity. The fruiting bodies were cleaned of soil and placed in pre-labelled plastic bags. At each collection site, composite soil samples were taken using a cylindrical drill with a diameter of 5 cm to a depth of 20 cm. Each composite sample consisted of five subsamples collected around the fruiting bodies (SOU 74.14-37-425:2006, 2006). Fungal species were identified and verified according to the accepted nomenclature (Index Fungorum, 2025).

In the laboratory, mushroom fruiting bodies were placed in Marinelli beakers with a volume of 1.000 cm^3, or in other calibrated containers, depending on the sample volume (135 or 500 cm^3). After measuring the activity concentration of ^{137}Cs in fresh mushroom samples, they were dried in a drying chamber for 72 hours, and measurements of radioactive contamination were repeated for the dried sampls. Soil samples were also dried in a drying chamber and homogenised before analysis. The activity concentration of ^{137}Cs in all samples was determined using a SEG-001 AKP-S-150 gamma spectrometer (Ukraine) equipped with a BDEG20-R1 scintillation detector (Ukraine). The measurement error of ^{137}Cs did not exceed 15%.

To evaluate the intensity of radionuclide uptake by mushroom fruiting bodies, the following parameters were calculated: the concentration ratio (CR) – defined as the ratio of the ^{137}Cs activity concentration in the fruiting bodies of a given mushroom species ($Bq \cdot kg^{-1}$) to the ^{137}Cs activity concentration in the soil ($Bq \cdot kg^{-1}$); and the aggregated transfer coefficients (*Tag*) – defined as the ratio of the ^{137}Cs activity concentration in the fruiting bodies of a given mushroom species ($Bq \cdot kg^{-1}$) to soil radioactive contamination density of ^{137}Cs ($kBq \cdot m^{-2}$). The latter parameter is expressed in the generally accepted units of $m^2 \cdot kg^{-1} \cdot 10^{-3}$ (Belli *et al.*, 1999; IAEA, 2009). The shrinkage coefficient of mushroom fruiting bodies was determined as the ratio of the fresh weight to the dry weight of the samples. Statistical analyses were performed using standard methods (Tsarenko *et al.*, 2000) with the MS Excel and Statistica 10 software packages.

RESULTS

The study area encompasses a wide variety of forest site conditions that differ in both soil fertility and moisture regime – ranging from nutrient-poor pine forests to rich oak forests, and from very dry habitats like sand dune tops to wet, swampy areas. In terms of soil fertility, the most widespread habitats in the Zhytomyr Polissia region are relatively infertile pine forest sites, occupying 329,779.2 ha (49.86%), and relatively fertile hardwood forest sites, covering 218,858.5 ha (33.09%) (Table 1). The moist relatively infertile pine forest is the dominant type of forest site conditions in the study region, accounting for 152,517.3 ha (23.06%) of the forested area. Other common site types include fresh relatively infertile pine forests (126,683.0 ha; 19.15%), moist relatively fertile forests (116,019.6 ha; 17.54%), and fresh relatively fertile forests (70,337.9 ha; 10.64%). The remaining forest site types each occupy less than 10% of the total forested area. These data indicate that moist relatively fertile forest sites are well represented within the study region and provide favourable conditions for the growth and diversity of edible mushrooms, making them an important focus for radioecological research.

***Table 1**. Distribution of forest areas of the State Specialised Forest Enterprise*

Forest site type	Area	
	ha	%
Dry infertile pine forest	8,457.9	1.28
Fresh infertile pine forest	48,168.1	7.29
Moist infertile pine forest	10,013.5	1.51
Damp infertile pine forest	5,461.8	0.83
Wet infertile pine forest	5,706.2	0.86
Infertile pine forests in total	**77,807.5**	**11.77**
Fresh relatively infertile pine forest	126,683.0	19.15
Moist relatively infertile pine forest	152,517.3	23.06
Damp relatively infertile pine forest	40,202.7	6.08
Wet relatively infertile pine forest	10,376.2	1.57
Relatively infertile pine forests in total	**329,779.2**	**49.86**
Fresh relatively fertile hardwood forest	70,337.9	10.64
Moist relatively fertile hardwood forest	116,019.6	17.54
Damp relatively fertile hardwood forest	29,855.7	4.51
Wet relatively fertile hardwood forest	2,645.3	0.40
Relatively fertile hardwood forests in total	**218,858.5**	**33.09**
Fresh fertile hardwood forest	17,874.6	2.70
Moist fertile hardwood forest	15,408.2	2.33
Damp fertile hardwood forest	1,615.9	0.24
Wet fertile hardwood forest	60.6	0.01
Fertile hardwood forests in total	**34,959.3**	**5.28**
Total	**661,404.5**	**100**

***Source:** created by the authors*

Values of ^{137}Cs concentration ratio in fresh mushroom fruiting bodies varied substantially among the studied species – from 7.4 ± 1.23 in *Paxillus involutus* to 0.01 ± 0.005 in *Lepista sordida* (Schumach.) Singer (Table 2). The highest value thus exceeded the lowest by a factor of approximately 740. A similarly wide range of this coefficient for ^{137}Cs in mushrooms has been reported in other forest site types (Krasnov *et al.*, 2006; Gabriel *et al.*, 2023). The maximum ^{137}Cs concentration ratios were recorded for *Paxillus involutus* (7.4 ± 1.23), *Imleria badia* (5.4 ± 0.62) and *Suillus luteus* (4.7 ± 0.02). Other species, including *Russula albonigra* (Krombh.) Fr., *R. delica* Fr., *Lactarius rufus*, and *Boletus edulis*, also exhibited elevated CR values, ranging from 1.4 ± 0.38 to 4.7 ± 0.02, and can therefore be classified as effective accumulators of ^{137}Cs. The markedly lower concentration ratios observed in other species may be attributed to differences in the depth of mycelium location and the ecological and biological characteristics of the fungi, particularly their affiliation with specific ecological and trophic groups (Krasnov *et al.*, 2006).

According to Table 3, the highest ^{137}Cs concentration ratio in dry mushroom fruiting bodies was observed in *Paxillus involutus* – 90.9 ± 16.54. Lower values were recorded for *Suillus luteus* (64.2 ± 3.78, representing 70.6% of the *P. involutus* value) and *Imleria badia* (63.7 ± 18.32, or 70.1%, respectively). The next two species showed considerably lower CR values: *Russula albonigra* – 36.6 ± 3.15 (40.3% of the *P. involutus* value) and *Lactarius rufus* – 32.1 ± 3.23 (35.3%, respectively).

Table 2. *Average values of ^{137}Cs concentration ratios in fresh fruiting bodies of mushrooms in moist relatively fertile forest sites in 2022-2023*

Mushroom species	Statistics of the distribution series				
	M	± m	± σ	V, %	P, %
Paxillus involutus	7.4	1.23	2.13	28.6	16.5
Imleria badia	5.4	0.62	1.38	25.7	11.5
Suillus luteus	4.7	0.02	0.03	0.6	0.3
Russula albonigra	2.5	0.40	0.80	31.6	15.8
Russula delica	2.2	0.14	0.25	11.4	6.6
Lactarius rufus	1.9	0.21	0.37	20.0	11.6
Boletus edulis	1.4	0.38	0.92	65.4	26.7
Armillaria mellea	0.5	0.01	0.01	2.6	1.5
Cantharellus cibarius	0.4	0.03	0.06	16.3	8.2
Amanita rubescens	0.2	0.03	0.05	23.4	13.5
Russula aeruginea	0.1	0.01	0.02	15.8	9.1
Hygrophorus eburneus	0.1	0.01	0.01	25.2	14.6
Chlorophyllum rhacodes	0.04	0.010	0.02	46.9	27.1
Paralepista flaccida	0.02	0.004	0.01	33.9	19.6
Lepista sordida	0.01	0.005	0.01	74.3	42.9

Source: *created by the authors*

Table 3. *Average values of ^{137}Cs concentration ratio in dry fruiting bodies of mushrooms in moist relatively fertile forest sites in 2022-2023*

Mushroom species	Statistics of the distribution series				
	M	± m	± σ	V, %	P, %
Paxillus involutus	90.9	16.54	28.6	31.5	18.2
Suillus luteus	64.2	3.78	6.6	10.2	5.9
Imleria badia	63.7	18.32	41.0	64.4	28.8
Russula albonigra	36.6	3.15	6.3	17.2	8.6
Lactarius rufus	32.1	3.23	5.6	17.4	10.1
Boletus edulis	15.0	4.66	11.4	76.3	31.2
Russula delica	10.7	0.92	1.6	14.9	8.6
Armillaria mellea	4.4	0.11	0.18	4.2	2.4
Cantharellus cibarius	2.3	0.25	0.51	21.7	10.9
Amanita rubescens	1.5	0.24	0.41	27.2	15.7
Russula aeruginea	1.2	0.13	0.23	19.3	11.2
Paralepista flaccida	0.94	0.112	0.19	20.7	12.0
Lepista sordida	0.26	0.049	0.08	32.8	19.0
Chlorophyllum rhacodes	0.18	0.053	0.09	50.2	29.0
Hygrophorus eburneus	0.15	0.020	0.04	23.8	13.8

Source: *created by the authors*

A comparison of the ranked series of species based on average CR values in fresh and dry mushroom fruiting bodies (Tables 2 and 3) reveals certain differences. In fresh mushrooms, the descending order of CR values was *Paxillus involutus* → *Imleria badia* → *Suillus luteus*, whereas in dry mushrooms the sequence changed to *Paxillus involutus* → *Suillus luteus* → *Imleria badia*. These discrepancies likely reflect differences in the moisture content of fruiting bodies among macromycete species, as supported by the pronounced variation in their drying coefficients (Table 4). The highest drying coefficient was recorded for *Paralepista flaccida* – 24.5 ± 1.39, while the lowest was observed for *Chlorophyllum rhacodes* (Vittad.) Vellinga, – 4.5 ± 0.08. It is also noteworthy that the coefficients of variation of this parameter were relatively high in many species, highlighting the importance of increasing the sample number in radioecological studies of mushroom contamination to ensure the reliability and representativeness of the results.

***Table 4**. Coefficients of drying of fungal fruiting bodies (times) in moist relatively fertile forest sites in 2022-2023*

Mushroom species	Statistics of the distribution series				
	M	± m	± σ	V, %	P, %
Paralepista flaccida	24.5	1.39	2.41	9.9	5.7
Russula aeruginea	24.2	0.46	0.80	3.3	1.9
Amanita rubescens	17.3	0.57	0.99	5.7	3.3
Armillaria mellea	14.4	1.45	2.50	17.4	10.0
Lepista sordida	13.8	1.26	2.18	15.8	9.1
Suillus luteus	11.6	0.67	1.16	10.0	5.8
Paxillus involutus	9.8	0.39	0.67	6.9	4.0
Imleria badia	9.3	0.95	2.13	22.8	10.2
Boletus edulis	8.9	0.47	1.16	13.1	5.3
Lactarius rufus	8.5	0.59	1.02	12.0	7.0
Russula albonigra	8.4	0.53	1.07	12.7	6.4
Cantharellus cibarius	7.5	0.11	0.22	3.1	1.5
Hygrophorus eburneus	4.9	0.19	0.32	6.5	3.8
Russula delica	4.8	0.10	0.17	3.6	2.1
Chlorophyllum rhacodes	4.5	0.08	0.14	3.1	1.8

***Source:** created by the authors*

For practical applications, particularly in identifying forest areas suitable for mushroom harvesting under conditions of radioactive contamination, the aggregated transfer coefficient (*Tag*) is used (Fig. 2).

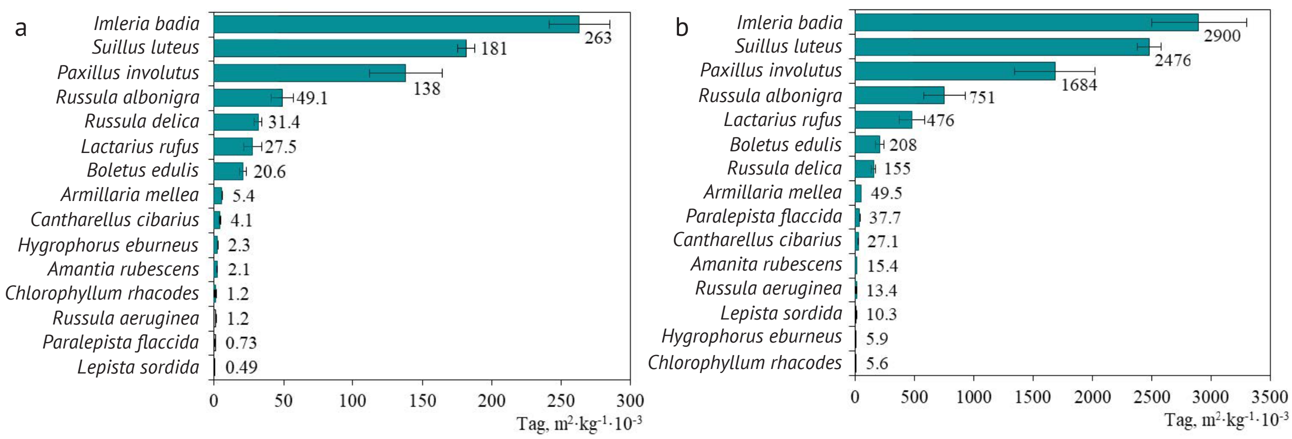

***Figure 2**. ^{137}Cs aggregated transfer coefficients from soil to dry (A) and fresh (B) mushrooms in moist relatively fertile forest sites in 2022-2023*

***Source:** created by the authors*

This indicator became widely applied following the Chornobyl accident and serves as a valuable tool for predicting radionuclide concentrations in mushrooms based on existing maps of forest radioactive contamination. The maximum ^{137}Cs aggregated transfer coefficient was recorded for *Imleria badia* – 263.3 ± 21.5 $m^2 \cdot kg^{-1} \cdot 10^{-3}$, while the minimum value was observed for *Lepista sordida* – 0.5 ± 0.20 $m^2 \cdot kg^{-1} \cdot 10^{-3}$. Thus, the maximum value exceeded the minimum by a factor of 526.6. The species exhibiting the highest transfer coefficients were *Imleria badia* (263.3 ± 21.5 $m^2 \cdot kg^{-1} \cdot 10^{-3}$), *Suillus luteus* (181.2 ± 6.2 $m^2 \cdot kg^{-1} \cdot 10^{-3}$), and *Paxillus involutus* (49.1 ± 7.9 $m^2 \cdot kg^{-1} \cdot 10^{-3}$).

To further elucidate interspecific differences, a cluster analysis was conducted incorporating the concentration ratios (CR), aggregated transfer coefficients (*Tag*) for both fresh and dry mushroom fruiting bodies, and the drying coefficient (Fig. 3). The cluster analysis revealed that the studied mushroom species can be grouped into four distinct clusters based on the above parameters. The first cluster comprises fungi with the smallest Euclidean distances, indicating the highest degree of similarity. This group includes *Paralepista flaccida*, *Lepista sordida*, *Russula aeruginea* Lindblad ex Fr., *Chlorophyllum rhacodes*, *Amanita rubescens*, *Hygrophorus eburneus* (Bull.) Fr., *Armillaria mellea*, and *Cantharellus cibarius*. This cluster contains the largest number of macromycete species. The second and third clusters each include two species: *Boletus edulis* and *Russula delica* in the second, and *Russula albonigra* and *Lactarius rufus* in the third. Minor differences in ^{137}Cs accumulation were observed between these two groups and the first cluster. The fourth cluster consists of *Suillus luteus*, *Paxillus involutus*, and *Imleria badia* – species identified as the most efficient accumulators of ^{137}Cs.

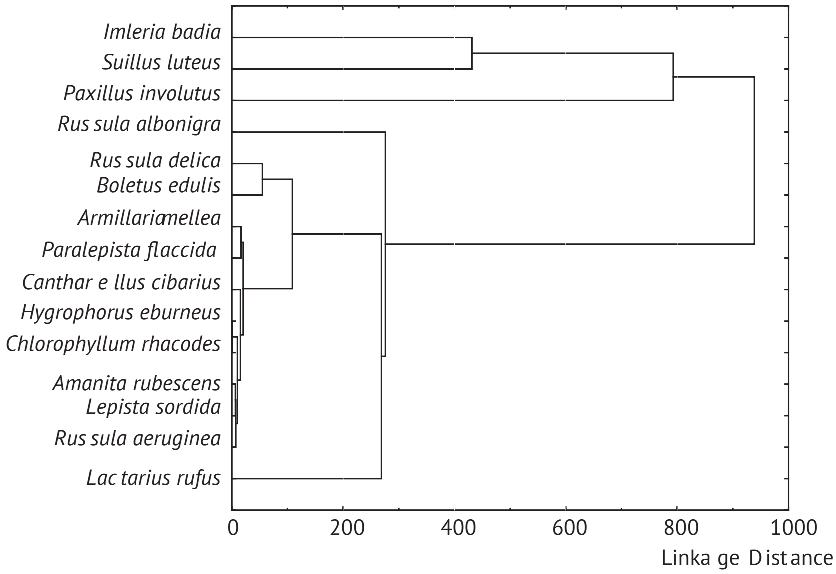

***Figure 3**. Dendrogram of similarity of mushroom species in moist relatively fertile forest sites based on radioecological characteristics*

***Source:** created by the authors*

The analysis revealed distinct species-specific patterns of ^{137}Cs accumulation in the fruiting bodies of mushrooms in moist relatively fertile forest sites. The study also confirmed the inherent challenges of monitoring radioactive contamination of macromycete fruiting bodies, which stem from both the irregular formation of mushrooms and the pronounced spatial heterogeneity of ^{137}Cs contamination of the area. The scientific novelty of this research lies in establishing a foundation for development of models describing radionuclide migration in forest ecosystems and for predicting the levels of radioactive contamination in edible mushrooms. From a practical standpoint, the results can be applied to improve the management and regulation of wild mushroom harvesting by integrating them with existing forest radioactive contamination maps, thereby supporting radiological safety and sustainable resource use.

DISCUSSION

Over 20 years after the Chornobyl accident in 1986, an international research team summarised the findings of studies on radionuclide migration in forest ecosystems and their accumulation in edible mushrooms (IAEA, 2009). The researchers concluded that radionuclide migration in forest ecosystems differs significantly from other environments, that the uptake of ^{137}Cs by mushrooms is generally high, and that the forest-derived food products – particularly mushrooms – represent an important source of internal radiation exposure for the population. It had been estimated that mushrooms may account for up to 56% of the daily intake of ^{137}Cs by humans, based on studies P. Strand *et al.* (1996).

Czech researchers O. Harkut *et al.* (2021) measured ^{137}Cs activity concentrations in three of the most common mushroom species – *Imleria badia*, *Russula ochroleuca* Fr., and *Armillaria mellea* (Vahl) P. Kumm. – in the

Opava region (Silesia) and the Beskids Mountains. The highest radionuclide concentrations were detected in the pilei of *Imleria badia* and *Russula ochroleuca* in the Opava region, reaching 11.8 and 8.77 kBq·kg^{-1}, respectively. However, calculations of the effective gamma radiation dose indicated that these levels do not pose a significant risk to public health, given the relatively low consumption of mushrooms by the local population. Similarly, low levels of radioactive contamination were reported by Slovak researchers P. Dvořák *et al.* (2020) in nine mushroom species collected from forests near Dolní Rožinka (Bohemian-Moravian Highlands), by Bulgarian scientists M. Lacheva *et al.* (2020), studying ^{137}Cs content in *Craterellus cornucopioides* (L.) Pers. in forests on Mount Batak and in various regions of the country by R. Lazarova & M. Hristozova (2025), and by Turkish researchers A. Pekşen *et al.* (2021) and A. Akkaya & S. Aktas (2025) investigating mushrooms from various regions of Turkey.

Studies conducted by L. Cui *et al.* (2020) and T. Matsuura (2021) in the 30 km exclusion zone of the Fukushima Daiichi Nuclear Power Plant, near the village of Kawauchi, revealed that ^{137}Cs activity concentrations in mushrooms exceeded Japan's permissible limit of 100 Bq·kg^{-1}. The differences varied by year: 75% of permissible limit in 2016, 48% in 2017, 84% in 2018, 79% in 2019. Based on these findings, the researchers recommended continuing radioecological monitoring of radionuclide content in mushrooms. Japanese researchers Y. Sasaki *et al.* (2025) have also studied the accumulation of ^{137}Cs in certain mushroom species grown at specially prepared sites under natural conditions. They confirmed significant levels of radioactive contamination in fungal fruiting bodies and emphasised the crucial role of moisture and organic matter in the uptake of radioactive isotopes from the soil.

The majority of publications concerning the radioactive contamination of mushrooms have originated from Ukraine, particularly during the first 15-20 years following the Chornobyl accident. In previous years, researchers V.P. Krasnov *et al.* (2006) summarised long-term investigations on this topic conducted in the Zhytomyr Polissia. Their studies examined, the intensity of radioactive contamination among mushrooms belonging to different ecological groups, the patterns of ^{137}Cs accumulation in the fruiting bodies of edible species across various forest site conditions, interspecies differences in radionuclide uptake, and the relationship between ^{137}Cs content in mushrooms and soil contamination density.

The results of a study of several mushroom species by O. Hromyk *et al.* (2024) – *Cantharellus cibarius*, *Boletus edulis*, and *Leccinum scabrum* (Bull.) Gray – conducted in the Kamin-Kashyrsky district of the Volyn region were published. The researchers compared the measured ^{137}Cs concentrations in mushrooms with the permissible levels of radioactive contamination and found exceedances in 6.8% of the samples. Despite the relatively low soil contamination levels in the forests of this district, the authors emphasised the need for continued radioecological monitoring of edible mushrooms. In the Zhytomyr region, O. Orlov *et al.* (2023) investigated ^{137}Cs accumulation in 18 mushroom species across different forest site conditions – namely fresh infertile pine sites and fresh and moist relatively infertile pine sites – at varying soil contamination densities (109 ± 13 to 410 ± 30 kBq·m^{-2}). The study revealed the highest ^{137}Cs aggregated transfer coefficients (*Tag*) in the fruiting bodies of symbiotrophic species such as *Cortinarius mucosus* (Bull.) J. Kickx f., *C. caperatus*, *Sarcodon imbricatus* (L.) P. Karst., *Imleria badia*, *Tricholoma equestre*, *Paxillus involutus*, *Hygrophorus hypothejus*, while the lowest values were observed in xylotrophic saprotrophs – *Armillaria mellea* and *Tapinella atrotomentosa*. In fresh infertile pine sites, increased ^{137}Cs accumulation was recorded in the following order: *Cortinarius mucosus* → *Hygrophorus hypothejus* → *Tricholoma equestre* (L.) P. Kumm. → *Sarcodon imbricatus*, with average *Tag* values ranging from 434.5 ± 23.25 to 205.4 ± 25 50 m^2·kg^{-1}·10^{-3}. The maximum value was observed for *Sarcodon imbricatus* (161.48 ± 10.415 m^2·kg^{-1}·10^{-3}) and the minimum for *Armillaria mellea* (2.26 ± 0.472 m^2·kg^{-1}·10^{-3}). Based on the intensity of ^{137}Cs accumulation in fruiting bodies, the top five species in this type of forest site conditions were ranked as follows: *Sarcodon imbricatus* → *Cortinarius caperatus* → *Paxillus involutus* → *Russula vinosa* Lindblad → *Lactarius rufus* (Scop.) Fr. In moist relatively infertile pine sites, the highest aggregated transfer coefficient was recorded for *Imleria badia* (110.8 ± 18.21 m^2·kg^{-1}·10^{-3}), while the lowest was found in *Leccinum scabrum* (9.2 ± 2.58 m^2·kg^{-1}·10^{-3}). The order of ^{137}Cs accumulation intensity (*Tag*) in the four most active species under these site conditions was as follows: *Imleria badia* → *Lactarius rufus* → *Cortinarius caperatus* → *Paxillus involutus* (Orlov *et al.*, 2023).

The accumulation of ^{137}Cs by various fungal species (54 species in total) has been investigated by J. Gabriel *et al.* (2023) in the forests managed by the Ivankivske Forest Management Unit of the State Specialised Forest Enterprise "Forests of Ukraine" (formerly the State Enterprise "Polissia Forest Economy"), located in the northern part of the Kyiv region, outside the 30 km exclusion zone of the Chornobyl Nuclear Power Plant. The study confirmed that mushrooms remain an important source of radionuclide intake into the human body (Grodzynska *et al.*, 2025). The highest radionuclide concentration ratios were recorded for *Suillus granulatus* (L.) Roussel (392.6), *Imleria badia* (164.3), and *Suillus luteus* (120.8). Similar research conducted in the Chernihiv region identified somewhat different species that actively accumulate ^{137}Cs. The concentration ratios for *Cortinarius semisanguineus* (Fr.) Gillet and *Paralepista gilva* (Pers.) Raithelh. exceeded 100, while those for *Cortinarius malicorus* Fr., *Cortinarius decipiens* (Pers.)

Zawadzki, *Sarcodon imbricatus*, and *Cortinarius praestans* (Cordier) Gillet ranged between 50 and 100. Overall, mushrooms demonstrate a high capacity to accumulate ^{137}Cs, with significant differences observed between species and environmental conditions. Despite generally low health risks in some regions, they remain an important source of internal radiation exposure, highlighting the need for continued monitoring.

CONCLUSIONS

The research data obtained over the 37 years since radionuclides entered forest ecosystems allow for several important scientific and practical conclusions. First, the intensity of ^{137}Cs accumulation in the fruiting bodies of wild mushrooms remains consistently high. The maximum concentration ratio of this radionuclide reached 7.4 ± 1.23 in *Paxillus involutus* for fresh mushrooms and 90.9 ± 16.54 for dry mushrooms in moist relatively fertile forest sites. Secondly, there are significant interspecific differences in the intensity of ^{137}Cs accumulation among mushroom species. Based on the concentration ratios for dry mushrooms, the species can be ranked in descending order as follows: *Paxillus involutus* → *Suillus luteus* → *Imleria badia* → *Russula albonigra* → *Lactarius rufus* →*Boletus edulis* → *Russula delica* → *Armillaria mellea* → *Cantharellus cibarius* → *Amanita rubescens* → *Russula aeruginea* → *Paralepista flaccida* → *Lepista sordida* → *Chlorophyllum rhacodes* → *Hygrophorus eburneus*. Thirdly, significant interspecies differences were also established in the drying coefficients of mushroom fruiting bodies. This indicator can serve as a useful predictor of potential radioactive contamination levels in mushrooms. Finally, the issue of radioactive contamination of mushrooms in the forests of Zhytomyr Polissia remains relevant and pressing, even decades after the Chornobyl Nuclear Power Plant accident. As prospects for further research, continued attention should be given to the long-term dynamics of radioactive contamination in forest ecosystems, particularly in relation to wild mushrooms. Future studies should focus on refining forest typology-based monitoring approaches to better predict the accumulation of radionuclides in different ecological conditions. The development of improved radioecological control strategies for the harvesting and consumption of edible mushrooms by local populations remains an important direction for ensuring environmental and public health safety.

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Особливості накопичення ^{137}Cs у плодових тілах грибів у вологих сугрудах лісів Житомирського Полісся

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Анотація. Метою дослідження було вивчення існуючих закономірностей радіоактивного забруднення грибів, що ростуть у вологих, відносно родючих лісових умовах. Дослідження були проведені у Житомирському Поліссі у поширеному, але мало вивченому у радіоекологічному відношенні типі лісорослинних умов – вологому сугруді. Було проведено порівняння показників, які характеризують інтенсивність накопичення ^{137}Cs у свіжих і сухих плодових тілах грибів – коефіцієнту накопичення та коефіцієнту переходу. Встановлено, що значні коефіцієнти накопичення ^{137}Cs у сухих грибах пояснюються значною усушкою плодових тіл. Виявлено значні міжвидові відмінності у накопиченні ^{137}Cs у плодових тілах грибів, на основі чого побудований рангований ряд видів, який демонструє інтенсивність накопичення радіонукліду. Величини коефіцієнтів накопичення ^{137}Cs у свіжих грибах коливаються у межах 0,01 ± 0,005 (*Lepista sordida*) – 7,4 ± 1,23 (*Paxillus involutus*). Перевищення максимального значення над мінімальним сягає 740 разів. Величини коефіцієнтів накопичення ^{137}Cs у сухих грибах коливаються від 0,15 ± 0,02 у *Hygrophorus eburneus* до 90,9 ± 16,54 у *Paxillus involutus*. У свіжих плодових тілах грибів ряд у порядку зменшення коефіцієнтів накопичення радіонукліду є наступним: *Paxillus involutus* → *Imleria badia* → *Suillus luteus*, а у сухих плодових тілах – *Paxillus involutus* → *Suillus luteus* → *Imleria badia*. Результати мають практичне значення для визначення лісових масивів, які потребують радіологічного контролю їстівних грибів при заготівлі. Матеріали досліджень можуть бути використані в практиці організації та втілення програми радіоекологічного моніторингу радіоактивно забруднених лісових екосистем

Ключові слова: тип лісорослинних умов; радіонуклід; питома активність; коефіцієнт накопичення; коефіцієнт переходу; коефіцієнт всихання

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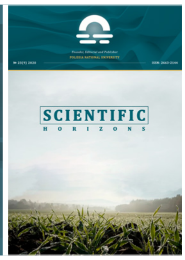

Analysis and classification of cleaning systems for visual sensors in agricultural machinery

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Abstract. This study aimed to examine and categorise several different cleaning system options for sensor units on agricultural machinery in order to determine how their performance impacts the potential for application in field operations. The research considers the degree of impact of different types of impurities on the efficiency of cleaning system operation (dust, dirt, crop residues and others, associated with the use of machines and equipment). The authors used monographic and abstract logical research methods to consolidate information on scientific publications about the technical solutions that had already been tried out in experimental setups and practice. The classification includes 4 types of the air pattern and has determined the main characteristics of cleaning systems in this mode. Two design configurations were considered in the description of structural implementation: integrated and external systems. The review results demonstrated the advantages of the integrated configuration due to its protection from external influences and maximum compactness. The operation of cleaning systems was divided into modes with constant and variable pulse duration. The efficiency analysis has shown that all types of modes have different performance depending on the type of pollution. In general, pulsed cleaning modes show better results for dry contamination, and cleaning modes with continuous water supply show higher efficiency in the case of wet contamination. The article also considers combined air-liquid cleaning systems, describes their design and the principle of operation. The study showed that air-based cleaning systems are integrated into machinery more effectively and can utilise existing components already incorporated by engineers for other functions, thereby making such solutions more economically efficient. Depending on the type of contamination, the air-blowing system can readily adjust the operating mode of the airflow to ensure maximum cleaning efficiency. The obtained results may be applied in the development and modernisation of sensor cleaning systems for modern agricultural machinery equipped with automatic and autonomous control elements. Based on scientific findings and independent experimental observations, the study examined which types of cleaning systems may be relevant during the operation

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of radar sensors in the field and determined the influence of contamination on guidance quality and the overall stability of system performance

Keywords: precision agriculture; radars; contamination; pneumatic system; self-propelled machinery; auto-steering system

INTRODUCTION

Information technology has become an important component of modern agriculture, aimed at meeting the growing food demands of the global population. With such limited possibilities for the expansion of agricultural lands, improving the productivity of their current use has acquired great importance in terms of agricultural development. According to data presented in the study by O. Nikoliuk *et al.* (2024), as of 2024, the total area of agricultural land in Ukraine amounted to 48,109.77 thousand hectares, of which 32,723.51 thousand hectares were arable land, while agricultural land accounted for approximately 79.65% of the total territory of the state. One of the approaches to increasing agricultural production, according to V.V. Adamchuk *et al.* (2026), is the implementation and application of precision agriculture technologies, which have demonstrated their effectiveness over an extended period.

An important component of precision agriculture systems is the automatic guidance of machinery, the purpose of which is to ensure accurate vehicle movement along predetermined trajectories in order to reduce time consumption, fuel and lubricant usage, and material costs. L. Babiy *et al.* (2026) reported a 10-15% increase in the productivity of agricultural machinery when navigation equipment using a Real-Time Kinematic (RTK) correction signal was employed. The study established that the implementation of auto-steering systems with RTK correction signals at large agricultural enterprises demonstrates a high level of efficiency and cost recovery. In particular, the use of such systems allows for an increase in the productivity of the machine by 10-15%, and on average reduces the use of seeds and fertilisers by 10-20%. Due to this, the payback period for the implementation of RTK equipment in machines becomes 2-4 years.

Auto-steering systems use data from various sensors to define the direction and trajectory of the machine. One such source is radar sensors, which monitor the distance between the wheel and the crop row and transmit data to the auto-steering controller for corresponding movement correction. Many manufacturers of self-propelled agricultural machinery create autonomous vehicles that are not operated by humans. Sensors for environmental monitoring in them are based on LiDAR and radar signals. The number of these sensors can reach several dozen, and the stability of their operation is of great importance. Methods of sensor and machine vision systems for guidance of machines along plant rows are widely used in the design of autonomous agricultural machinery and mobile robotic platforms for the purpose of providing the movement of the vehicle with the required precision (under field conditions) (Shi *et al.*, 2023).

As described in the study by S. Debnath *et al.* (2023), light detection and ranging (LiDAR) sensors are considered the most important for the agriculture sector, as they are considered as nondestructive means of remote sensing (not depending on the lighting conditions). Furthermore, the accuracy of the data provided is higher than that of other digital sensing methods. The application of LiDAR in agriculture was also studied by M.R. Karim *et al.* (2024), who emphasised that LiDAR sensors have great potential for use in identifying crops, specifically via the estimation of crop height, the estimation of crop canopies and the spacing between plants and crop rows, and by identifying the agricultural operating environment (field contours, ridges, obstacles faced by agricultural machinery).

At the same time, during operation, sensors are exposed to various forms of contamination, including dust, soil particles, plant residues, and moisture. The study by O. Artyukh *et al.* (2025) described the problem of contamination affecting LiDAR systems, radar sensors, and cameras installed on autonomous vehicles. The authors report that over the period 2020-2025, there was a high level of improvement in the reliability of system perception in challenging conditions, although ensuring flawless work in challenging weather conditions, such as heavy rain, snowfall, fog and poor lighting, is still one of the key challenges. Radar systems can deal with small amounts of contamination using software; however, in challenging conditions, it may be difficult or even impossible to operate machines.

When similar technologies are used on agricultural machinery, contaminants on sensors can also reduce the accuracy of distance readings to crops or obstacles and eventually cause sensors to fail (Vargas *et al.*, 2021; Matos *et al.*, 2024). This, in turn, results in lower automatic steering system efficiency and in lower economic gains from the modernisation of agricultural machinery. Thus, the analysis of the cleaning systems that could be used to solve this problem is a scientifically important topic that is in need of further development and creation of effective engineering solutions for ensuring stable sensors work in fields (Aarif *et al.*, 2025). Significant attention should be paid to the investigation of various cleaning methods, including pneumatic, hydrodynamic and integrated ones that would ensure the complete removal of dust, dirt and moisture from sensors without disrupting the technological process. Pneumatic systems that use compressed air are the most promising. These systems are simple to operate and can react quickly, and can easily be integrated into the existing machine designs, but the parameters of air supply to the cleaning system and the energy consumption need to be improved.

It is also essential to determine the structural integration of the system itself into sensor or machine units to ensure autonomous operation and eliminate the influence of human factors. In addition, it is advisable to consider the cost-effectiveness of implementing such solutions, as the installation of such systems should not only increase the reliability of the operation of machinery, but also pay off quickly as a result of reducing the frequency of work stoppages and increasing the operational accuracy and reducing maintenance costs. In this regard, the assessment of the existing pneumatic systems for cleaning sensors and the development of a general classification of such systems are important research topics. This approach helps boost the effectiveness of automatic guidance and, thus, promotes overall progress in precision farming. Therefore, this study aimed to analyse and classify sensor cleaning methods used in agricultural machinery, and then to determine their operational effectiveness for potential use during field work.

MATERIALS AND METHODS

The study was based on a review-based and analytical approach with the use of methods for theoretical generalisation and comparative analysis. The basis for the research was the systematisation of scientific and technical literature, the data of experimental studies, published in open access sources and the authors' own observations in the course of agricultural machinery operation. The study procedure includes the following steps.

At the first stage, information sources were selected according to the following criteria: relevance, with emphasis on publications issued mainly within the past five years; scientific or practical significance; the presence of descriptions of sensor cleaning system designs or their individual components; and relevance to the operating conditions of agricultural machinery. Firstly, the following sources were selected: scientific articles, patents, technical reports and materials provided by manufacturers. Secondly, a comparative analysis of selected sources was performed according to the main parameters: design features of cleaning systems, operating principle, type of working medium used (air, liquid and combined), and operating modes. For more objective analysis in all studied sources, a unified set of indicators was selected that determines the effectiveness of cleaning the various types of contamination from sensors, the efficiency of cleaning, energy consumption, design complexity, possibility of introduction and operation reliability. During the third stage, the obtained results were generalised, which made it possible to identify typical technical solutions and develop approaches to the classification of sensor cleaning systems. Abstract-logical methods are used during generalisation of data to systematise heterogeneous content and identify relations between system structural parameters and their operational effectiveness. Then systems were classified according to such criteria as the air flow pattern, the form of construction scheme, operating mode and type of working media. The classification was based on analysis of specific technical solutions, which occur in different sources and are adapted to agricultural machinery operation conditions.

The study also included a comparison of the effectiveness of different cleaning systems using generalised indicators obtained from literature sources. The basic parameters of cleaning system classification were: degree of dry dust removal, plant debris removal, wet and adhesive contaminants removal, energy consumption (compressor power), cleaning cycle time, and adaptability of a system to changing operating conditions. To quantify the efficiency value of sensors' cleaning systems, the data on experimental studies obtained in the analysed scientific literature were used, e.g. 85%-95% of cleaning of the dry dust from a dust air stream; 95%-98% in combined cleaning systems. In addition, it was also used the data of field observations described in the earlier study of I. Osadchyi (2025), which made it possible to consider the practical aspects of applying cleaning systems more carefully, particularly the impact of the operating mode on the efficiency of cleaning different types of contamination and the real feasibility of using pneumatic cleaning systems in operation. To solve the issue of cleaning sensors, cameras, and radar detectors in agricultural machinery, it was investigated how the current structural solutions of the machines can be applied to this task. As part of the study on cleaning sensors, video cameras and radar scanners installed on an agricultural machine, the scientists carried out research on the structural parts of these vehicles, which can be used as elements of a cleaning system. It was established that most self-propelled agricultural machines are equipped with pneumatic systems for suspension, purging the boom, performing maintenance, inflating tyres, and other auxiliary functions. The use of such pneumatic systems makes it possible to use the existing energy source to supply compressed air for sensor cleaning without greatly complicating the structure of the machines.

RESULTS AND DISCUSSION

The first assumption for further consideration of a sensor cleaning system is that most self-propelled agricultural machines are equipped with pneumatic systems for suspension, purging the boom, performing maintenance, inflating tyres, and other auxiliary functions. This creates the possibility of using the existing compressed-air network as a power source for sensor cleaning without complicating the design of the machine. Therefore, it can be concluded that the pneumatic cleaning system is a technically and economically justified solution for its introduction into agricultural machines. Due to the above, in the proposed classification, this type takes precedence. Based on the systematisation and generalisation of the resulting data using an abstract-logical approach, a classification of the main types of cleaning systems of sensors adapted for the purpose of use in agricultural machines has been developed (Fig. 1). In the proposed classification system, information on common technical solutions for cleaning sensors in various sources (scientific articles, patents, technical documentation) was generalised, according to the authors' observations. Classification is implemented according to the spray pattern, configuration, operating modes, and type of the working-medium feed. This approach allows for the systematisation of sensor cleaning systems according to key characteristics of the performance and implementation areas.

According to the spray pattern. The first criterion (and one of the main ones) is the shape of the flow from the nozzle, as this affects the efficiency of the process of cleaning the sensors from various contaminants. The nozzles provide direction and characteristics of the flow as it exits the enclosed duct. When passing the medium through the nozzle, the flow velocity at the exit increases and its direction changes into different shapes depending on the shape of the outlet. These shapes are conical spray, flat spray, and circular spray. The types of spray patterns are shown in Figure 2, and the specific applications of each are summarised in Table 1.

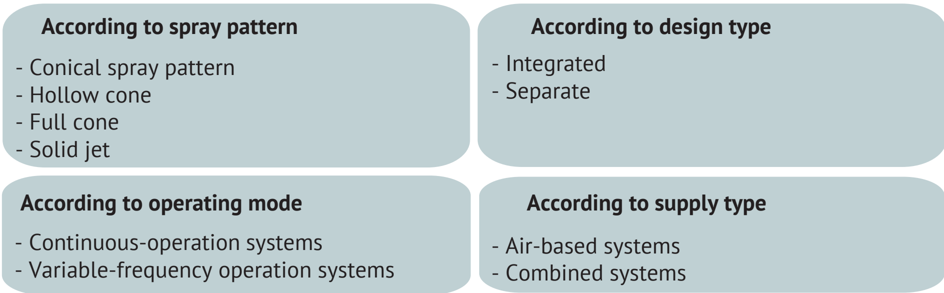

***Figure 1**. Classification of cleaning systems according to different criteria*
***Source:** developed by the author*

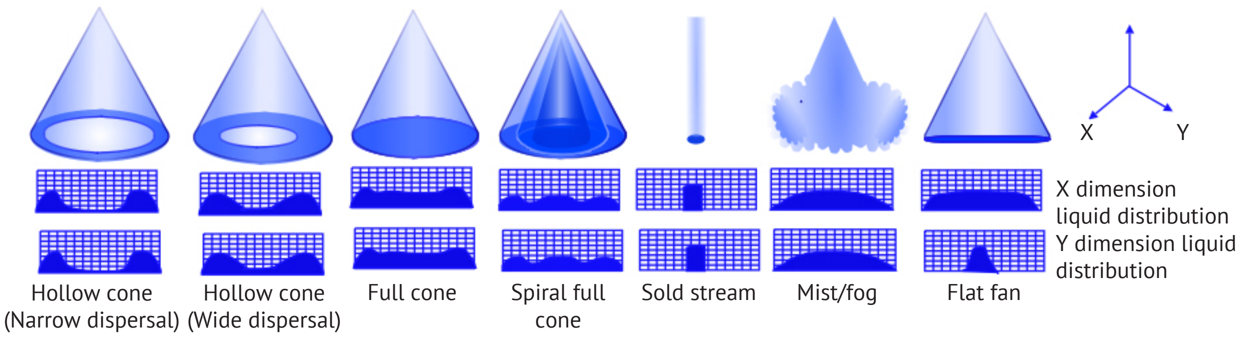

***Figure 2**. Spray pattern types of nozzles*
***Source:** The Spray Nozzle People (n.d.)*

***Table 1**. Application characteristics of different spray patterns*

Type	Characteristics	Field of application
Conical spray pattern	Produces a cone-shaped airflow; provides uniform coverage over a large area with a spray angle of 15°-145°; formed through a simple outlet or deflector surface.	Cleaning of wide optical surfaces, front-facing cameras, and radar antennas with flat geometry.
Hollow cone	Concentrates airflow along the cone perimeter in a fan-shaped pattern; formed by axial, tangential, or spiral nozzles; characterised by high performance but increased air consumption.	Removal of contaminants from the edges of optical elements and wide LiDAR panels.
Full cone	Ensures uniform airflow distribution across the entire cone area; spray angle of 30°-170°; formed by axial, tangential, or spiral nozzles.	Cleaning of flat camera surfaces, wide LiDAR windows, and surfaces with evenly distributed contamination.

Table 1. Continued

Type	Characteristics	Field of application
Solid jet	Narrow, focused airflow; low air consumption; high energy concentration over a small area; effective in pulsed operation mode.	Localised cleaning of small optical elements; used in combination with wide spray patterns or specialised lens surfaces.

Source: *developed by the author*

A conical spray pattern forms a cone-like airflow and has a homogeneous airflow on a large surface area of the detector and a defined opening angle. The spray angles for flat spray patterns can vary from 15° to 145° depending on the nozzle design (Fig. 3). The spray pattern can be obtained by using a simple orifice or a jet deflection on a specially shaped reflective surface.

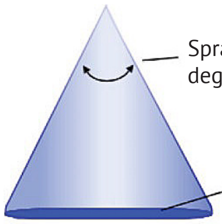

Figure 3*. Conical spray pattern*
Source: *The Spray Nozzle People (n.d.)*

A hollow cone is a fan-like airflow spray pattern (Fig. 4). In the hollow cone, the air flow is concentrated on the contour of the cone, making it ideal for cleaning the edges of optical elements. Similar to other spray patterns, spray angles may vary from 15° to 145° depending on nozzle design. The spray pattern can also be generated by using a simple orifice or a jet deflection on a specially shaped reflective surface (Fig. 4).

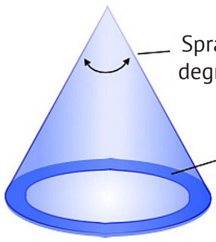

Figure 4*. Hollow cone*
Source: *The Spray Nozzle People (n.d.)*

The hollow cone pattern is produced by three main types of nozzle designs:

- Axial swirl nozzles – internal channels (vanes) impart a swirling motion to the airflow before it exits the orifice.
- Tangential swirl nozzles – airflow is set into rotational (vortical) motion due to an offset outlet positioned perpendicular to the feed channel.
- Spiral nozzles – airflow impacts a protruding spiral surface, which breaks the flow into finer particles.

These spray patterns are used to clean the front-view camera, wide LiDAR panel, and radar antenna of flat geometry. A spray pattern has the advantages of high cleaning performance and uniformity for cleaning on a large surface area of the target object, but it also has disadvantages such as increased air flow and possible dispersion of contaminants to the neighbouring surface area. A full cone spray pattern is a spray pattern that gives a uniform airflow over the entire area of the cone. The pattern is well-suited for cleaning the flat camera surfaces and wide windows of LiDARs. In the study by S. Son *et al.* (2024) on the optimisation of the spray cleaning performance for LiDAR sensors, the full cone spray pattern was used. The cone angle usually varies between 30° and 170° depending on nozzle design (Fig. 5). The full cone can be formed using the axial and tangential swirl nozzle and spiral nozzle.

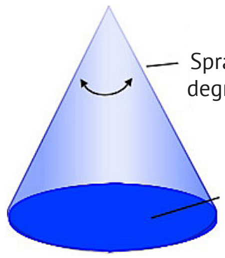

Figure 5*. Full cone*
Source: *The Spray Nozzle People (n.d.)*

A solid jet is a spray pattern that has a concentrated airflow in a narrow stream. A solid stream is a concentrated stream of air with simple geometry. This is produced by directing the air into an orifice of special shape, which forms the solid stream as a narrow jet. The main advantage of such a spray pattern is its high impact intensity in a small area, as well as its low air consumption. In the pulsed mode, it has a pronounced mechanical cleaning effect. Its main limitation is the very small working area, which requires its use in combination with specialised lens-based surfaces or together with wider spray patterns (Fig. 6).

Figure 6*. Solid jet*
Source: *Lechler (n.d.)*

According to the design type. According to the structural layout, pneumatic cleaning systems can be classified into two main types: the integrated and the separate. In an integrated design, the lens (an optical element in the sensor) and cleaning unit are located in the same enclosure. It is possible in two variants: (1) in the form of a monolithic single unit located inside the machine structure; (2) in the form of a separate unit located outside the structure. The first type describes a single monolithic part that is included in the machine body, where the cleaning nozzles and the sensor lens are part of the same unit, which is integrated into the casing or chassis of the vehicle. The air channels are also included in the body of the vehicle. An example of this kind of solution is presented in the patent WO2016045828, showing a device in the form of a compact module with an integrated air cleaning mechanism (Fig. 7).

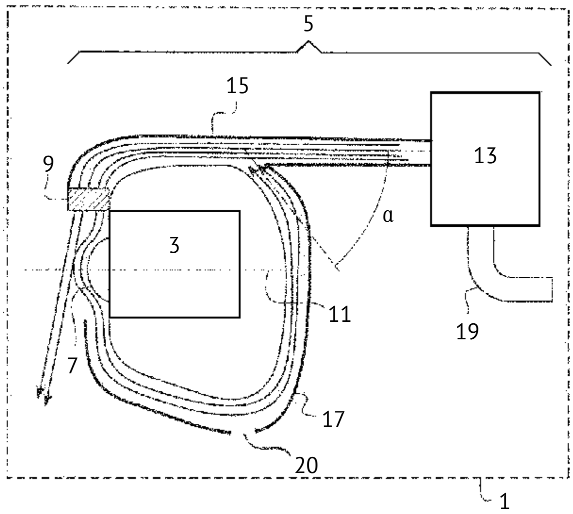

Figure 7*. Design of an integrated cleaning system*
Note: *3 – optical sensor; 5 – protective housing for the optical sensor; 7 – convex optics; 9 – nozzle; 11 – optical axis; 13 – air pump; 15 – outlet channel; 17 – suction channel; 19 – air inlet; 20 – condensate drainage opening*
Source: *PatentScope (n.d.a)*

Invention relates to a device for protecting an optical sensor including at least one nozzle (9) for jetting air in front of the optical sensor (3), wherein said jet nozzle is arranged at one side of the optical sensor and fluid connected to an air pump (13) via an exhaust duct (15) such that an air jet emitted by said jet nozzle is parallel to the optical sensor surface, and at least one suction duct (17) is arranged at a side of the optical sensor opposite to said jet nozzle. The suction duct is fluid-connected to the pump exhaust duct downstream of the pump, such that suction in the suction duct is produced by the Venturi effect. The main advantages of this solution are maximum compactness and protection against external influences.

The second type is an externally located additional separate unit, where the sensor and cleaning device make up a separate unit, which is mounted on the outside of the machine, the nozzles being mounted around or above the lens. Patent WO2018130610 (PatentScope, n.d.b) served as a sample to create a separate unit design with telescopic nozzles (Fig. 8).

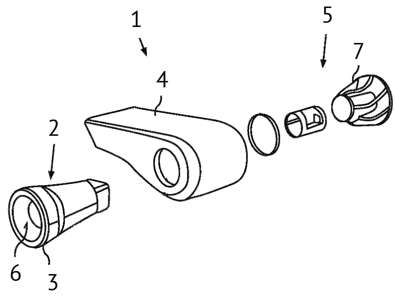

Figure 8*. Design of a separate cleaning system*
Note: *1 – camera for a motor vehicle; 2 – camera for detecting the surrounding environment; 3 – lens unit; 4 – camera holder; 5 – cleaning device; 6 – external surface of the lens unit; 7 – fan element*
Source: *PatentScope (n.d.b)*

The invention relates to a camera (1) for a motor vehicle, comprising a camera (2) for detecting the surrounding environment of the vehicle, where the camera (2) includes a lens unit (3) with at least one lens, a holder (4) for securing the camera (2) to the vehicle, and a cleaning device (5) for cleaning the external surface (6) of the lens unit (3). The cleaning device (5) comprises a fan element (7) mounted on the holder (4) and designed to generate an airflow for cleaning the external surface (6) of the lens unit (3). Among the main advantages of this solution are simplicity of installation and dismantling, the ability to quickly change in case of failure, and versatility in choosing the location on the machine.

Separate design type. The modular type is a set of independent parts, including a lens exposed to the environment and a nozzle system mounted separately. In particular, this principle is used in the cleaning system of a radar camera for the sprayer AGCO/Fendt RoGator 900. The distinctive feature of this configuration is that the sensor is installed at one point, while the nozzles are at a distance and are connected by air lines to the compressor. The separate configuration allows maximum freedom of sensor and equipment placement, adjustment of the angle of incidence of the airflow on the sensor, upgrade of existing sensor systems, independent maintenance and repair of sensors and the cleaning system itself, and the implementation of centralised systems with a distribution system to service several sensors. In agricultural machinery, this type of configuration is common due to the need to protect expensive sensors from mechanical damage, as well as the ability to position the sensor in an optimal position with respect to the working space (Fig. 9). The example in the Raven Industries Manual (n.d.) shows how nozzles were placed taking into account the direction of movement of contamination and the optimal position of sensors relative to the object being scanned during operational tasks. The advantage of this solution is that field maintenance can be carried out without the use of special equipment, as can be seen in the patent WO2016045828, WO2018130610 (PatentScope, n.d.a.; n.d.b).

Figure 9*. Sensor with a separate cleaning configuration*
Source: *Raven Industries Manual (n.d.)*

According to the operating mode variability. By the type of variability of the operating mode, these systems can be divided into systems operating in a constant mode and variable-frequency operation systems. According to G. Sanders & A.V. Keeping (2024), constant-operation systems are characterised by continuous air supply during machine operation, constant pressure and flow velocity, and the formation of an air curtain in front of the sensors, providing uninterrupted protection against contamination. These systems are used in conditions of heavy contamination of working surfaces of the sensors (grain harvesting, processing of straw), in conditions of high speed of movement of agricultural machines as well as critical sensors where loss of visibility even for a short time is unacceptable, for example, sensors of fully and partially autonomous machines of the 4-5th SAE level of automation (Komesker *et al.*, 2024; Liu *et al.*, 2025). The advantages of systems operating in a constant mode are complete protection of sensors of all types of contamination, the lack of switching cycles "on/off", increasing the reliability of operation, simplifying the system, not requiring a complex algorithm for turning on the sensors, as well as the possibility of creating a prevention barrier, preventing contamination deposition on optical surfaces of the sensors. The main drawback of the system is high energy consumption of the compressor (it can reach 3-5 kW in continuous power), and high wear of the machine. In order to reduce the energy consumption of constant operation systems, new technical solutions are used, in particular aerodynamic air knives, instead of traditional nozzles that increase the effectiveness of using compressed air.

The main feature of systems operating in variable frequency mode is that the cleaning operation is periodically carried out, with the possibility of setting the frequency, changing the intensity of the cleaning process depending on the degree of contamination, and setting a certain mode of operation of the sensor depending on the conditions in which the system operates. Its main advantage is energy savings up to 60% compared with systems operating in a constant mode. On the other hand, variablefrequency systems have disadvantages: a relatively complex control system that requires the creation of programmes and parameter configuration (Market Research Future, 2024). The variablefrequency system operates on the principle of pulse modulation, as illustrated in Figure 10.

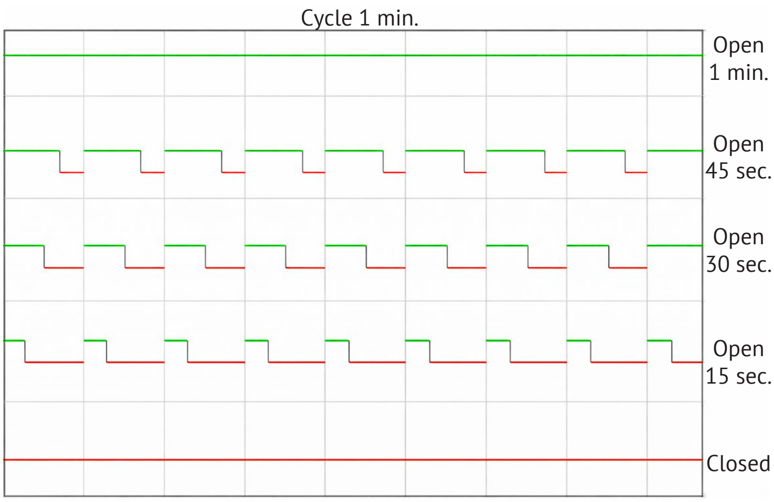

Figure 10*. Operating cycles of the air valve*
Source: *X. Fan (2020)*

According to the type of medium supply. The air-based systems use only clean air to clean sensors. The degree of efficiency in cleaning different types of contamination is largely dependent on their nature. It was determined that it is possible to clean 85-95% of dry dust and 70-80% of plant debris in a single cleaning cycle, while wet contamination in the form of small quantities of mud can be cleaned to only 30-70%; in the case of wet contamination in the form of organic matter (which is very adhesive), this can range from 20% to 60% (Son *et al.*, 2023). However, the main benefits of the air-based systems can be described as the lack of consumables, i.e. liquids, easy maintenance of the system and its operation at sub-zero temperatures, environmental friendliness, high-frequency operation capability, and absence of traces or blurring on the sensor. (Acuity Laser, 2025). At the same time, the system also has significant limitations, in particular, low effectiveness against sticky and wet contamination, high energy consumption, and the requirement for a powerful compressor. The air-based systems are more suitable in dry seasons and regions with little humidity in the air, dry regions or areas with a high amount of sandy soil, during operations in high dustiness (e.g. ploughing, land cultivation or tilling), before cleaning sensors using liquid-based sensor cleaning systems on autonomous machines.

Combined air–liquid systems integrate the positive features of both air and liquid-based systems to achieve maximum performance (XenomatiX, 2022). Such systems can be built based on different sequential principles. Air pre-blowing can be applied for 0.5-1 seconds for cleaning large and dry contaminants, followed by liquid spraying for 1-2 seconds for removing sticky contaminants, finishing with air blowing for 1-2 seconds to remove liquids. The second configuration is based on simultaneous operation, where the liquid is delivered as a fine aerosol, and the airflow simultaneously disperses the liquid and removes contaminants using specialised dual-component nozzles. The third one is adaptive, which means the system will automatically choose the appropriate mode depending on the type of contaminants: dry dust – air mode, sticky contaminants – air–liquid combined mode, and critical contamination – liquid cleaning (Solero Technologies, n.d.). The component base of the combined systems includes the components of the air-based system and adds a liquid tank, liquid pump, heating system (optional), dual nozzles (separate), nozzle for air and liquid, liquid sensors, and a controller of operating modes.

The working fluid can be used for different purposes: distilled water, water solutions with added detergents or surfactants, water solutions with surfactants that reduce the temperature needed for water freezing, or alcohol-based water solutions for low-temperature operation. In the research by S. Son *et al.* (2024), the performance of the liquid cleaning system is investigated by examining various influencing factors such as washer pressure, spray time, spray angle, and spray distance. In this regard, it was shown that the degree of cleaning increased with the increase in pressure and spray time. The highest percentage of cleanability was achieved when the point of impact was located at a distance of 10 mm, and the angle of spraying in the range from 20° to 30° (Fig. 11). A fan-type washer nozzle with a spraying angle of 60° was applied in the experiment, which is typical of most washer nozzles.

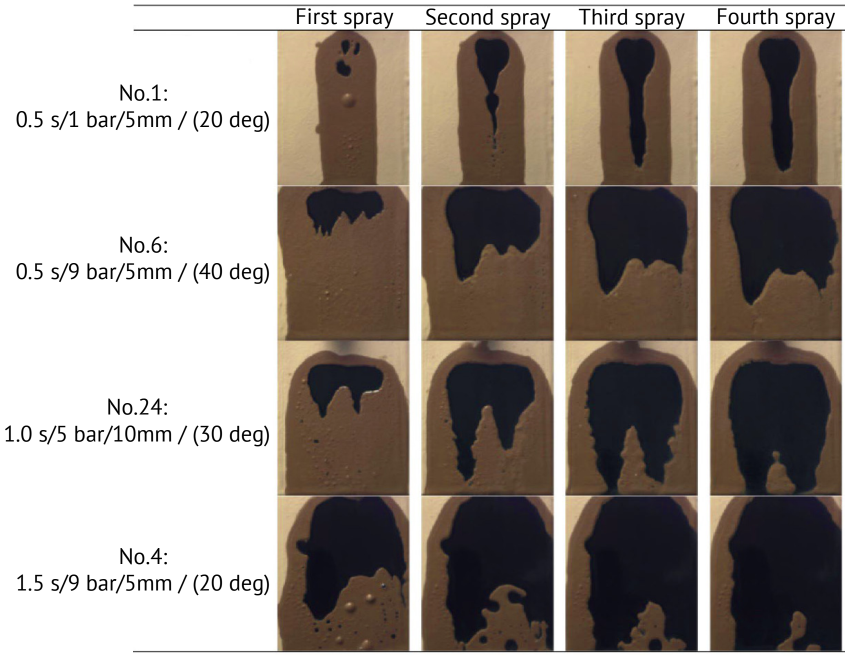

***Figure 11**. Sample photographs of experimental results under four standard conditions*

***Source:** S. Son et al. (2024)*

The main advantages of these systems are their universality, high efficiency of cleaning different types of contaminants, the possibility of operation in a wide temperature range, and economic consumption of liquid during final blowout with air. However, the disadvantages of these systems are a more complex design and cost, the need to maintain two subsystems, and greater mass and dimensional characteristics compared with simple systems using only air for cleaning (Valeo, 2024). A drawback of combined systems is a temporary deterioration of the sensor performance due to the presence of water droplets on it, which substantially reduces the visibility of the background and causes blurred image artefacts. Such problems were discussed in the study of R. Qian *et al*. (2018), where the authors noted that areas occluded by droplets cannot be detected by cameras, and information about the background is mostly lost. To solve this problem, generative neural networks based on machine learning methods are used.

Examples of practical implementation of combined systems of sensor cleaning are numerous technical solutions developed by leading manufacturers for the automotive industry. Some of them use separate nozzles with a liquid spray element and an additional air channel for drying off the remaining liquid. This type of system provides effective cleaning and drying of the sensor surface. Such cleaning systems are designed for cleaning the window of LiDAR under various weather conditions using a combination of water and air. In this case, the system cleans rainwater, dust, and other contaminants. It may also have a defrosting function, allowing it to operate in cold weather. Some other systems are equipped with nozzles with adjustable pressure and variable flow intensity to ensure the economic consumption of liquid and the stable operation of the sensor at high vehicle speeds. In modern industrial designs, an adaptive system of sensor cleaning is used in which the pressure of spraying and the flow rate are automatically adjusted depending on the degree of the sensor surface contamination, as well as the operating mode of the system (Vitesco Technologies, 2024).

Combined systems are most appropriately applied under conditions of variable weather factors and high levels of contamination. Such systems are especially relevant for autonomous machines of classes 3-5, for which it is important to maintain continuous, reliable operation of sensors and for systems that have long-term operation cycles, which exclude the possibility of manual cleaning of equipment. Similar operating conditions apply to military machines that have been retrofitted to operate autonomously. Solutions for this type of equipment are described in an article by a manufacturer of electronic surveillance and control systems (Ascencione, 2024).

In terms of recommendations for the usage of different types of systems, air systems are the best choice for dry conditions; dry mineral dust; where water is unavailable; where weight constraints exist; where air temperature is below zero, and if no heating system is installed for the sensor. In contrast, combined systems are appropriate for varying operating conditions, when there are adhesive organic contaminants on the sensors; when a high degree of reliability is required for the sensor operation; during long operating cycles; and when machines operate autonomously without operator intervention. Washing system companies are developing more advanced and "smart" sensor cleaning systems that can keep more than 10 objects clean using a water pressure of up to 7 bar and are built around a single integrated infrastructure (Valeo, n.d.; Solero Technologies, n.d.; Schafer Technologies, n.d.). Thus, the current state of development of sensor cleaning systems is typical of agricultural machinery development: from simple devices such as air nozzles to multifunctional combined solutions with centralised washing and cleaning systems with separate infrastructure. Further development of such systems towards higher levels of automation and reduced energy consumption is a necessary condition for the reliable operation of autonomous agricultural machinery at SAE levels 3-5.

CONCLUSIONS

In conclusion, based on the results of the analytical review and comparative analysis of the reviewed scientific and technical literature, it was found that pneumatic systems for cleaning sensors are classified by the following key parameters: design, air flow pattern, modes of operation, and type of working substance. At the same time, these parameters play a significant role in the effectiveness of pneumatic cleaning systems under different operating conditions. The review results show that the stability and efficiency of visual, radar, and LiDAR sensors for agricultural machinery directly depend on the cleanliness of cleaning systems. Contamination of the sensor in the form of dust, mud, plant residues, moisture and others has a negative impact on sensor operation, reducing the quality of transmitted signals and accuracy of measurements. This, in turn, reduces the efficiency of automatic steering systems for agricultural machines. During the study, existing technical solutions were analysed and generalised, and classified based on the most relevant criteria: airflow pattern, structural configuration, operating modes, and type of working medium. It has been established that pneumatic systems are structurally simple, do not rely on consumables and are effective at removing dry contaminants; however, their effectiveness is significantly reduced in the presence of moisture or sticky substances. Conversely, the most versatile and efficient are the combined air-liquid systems that can effectively clean sensors from various types of contamination due to the complex mechanical effect of the airflow and the physicochemical effect of the liquid.

The study results showed that the appropriateness of a particular type of system for cleaning depends on the machine's operating conditions, the nature of contamination, continuity of sensor operation, and the constraints of machine operation. Using existing systems based on a pneumatic drive for cleaning sensors in agricultural machinery does not significantly change the machine's design, which is a positive factor for implementation. Future studies should focus on the development of adaptive intelligent systems for sensor cleaning, which automatically determine the type of contamination and degree of contamination and select optimal operating modes for cleaning systems. Additional experimental research under field conditions will be necessary to adjust energy parameters, optimise the design of the nozzles and air and liquid supply modes. Attention should also be focused on the integration of the cleaning system with the data processing algorithms of the sensors, which should provide more reliable operation of automatic steering systems, increasing the efficiency of agricultural machinery.

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CONFLICT OF INTEREST

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Аналіз та класифікація систем очистки візуальних датчиків сільськогосподарських машин

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Анотація. Метою дослідження було проаналізувати та класифікувати варіанти систем очистки датчиків, які встановлюються на сільськогосподарських машинах, якість роботи яких напряму впливає на можливість використання техніки в польових роботах. Проаналізовано вплив різних типів забруднень на ефективність систем очищення датчиків пилом, брудом, пожнивними рештками та іншими матеріалами, які супроводжуються експлуатацією машин та обладнання. Під час дослідження застосовувалися монографічний та абстрактно-логічний методи, що дозволили скомпонувати наукові джерела, в яких описувалися технічні рішення, випробувані в лабораторних та практичних середовищах. Проведено класифікацію систем очищення за формою факела, де описано 4 типів з основними характеристиками. В описі конструктивного виконання було розглянуто два варіанти – інтегрований та зовнішній. Результати огляду показали перевагу інтегрованої конструкції через свою захищеність від зовнішніх впливів та максимальну компактність. Роботу систем очистки було поділено на режими з постійним та змінним часом пульсації. Кожен з режимів має свою ефективність в залежності від типу забруднення. Встановлено, що з сухим забрудненням ефективніше працювати пульсуючим режимом, тоді як з вологим забрудненням – режимом постійної роботи. Також розглядалися комбіновані повітряно-рідинні системи, їх конструктивні особливості з описом принципів роботи. Дослідження показало, що повітряні системи очищення найкраще інтегруються на техніку та можуть використовувати наявні компоненти, які передбачені інженерами для виконання інших задач, що, в свою чергу, робить таке рішення економічно ефективнішим. В залежності від типів забруднень, система обдуву може легко змінювати режим роботи повітряного обдуву та забезпечити максимальну ефективність очистки. Отримані результати можуть бути використані при розробці та модернізації систем очищення датчиків у сучасній сільськогосподарській техніці з елементами автоматичного та автономного керування. Базуючись на наукових та власних дослідах, вивчити які типи систем очистки можуть бути актуальними під час роботи радарних датчиків на полі та визначити вплив забруднень на якість ведення та стабільність роботи системи в цілому

Ключові слова: точне землеробство; радари; забруднення; пневматична система; самохідна техніка; система автоводіння

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