UDC 633.31:631.67:504.5:546.3 (477.74)
DOI https://doi.org/10.32848/0135-2369.2026.86.3

ASSESSMENT AND CONTROL OF HEAVY METAL CONTAMINATION IN ALFALFA GREEN MASS YIELD ON IRRIGATED LANDS OF ODESA REGION

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Problem Statement. Irrigation is one of the key factors contributing to the stabilization of forage crop production under the arid conditions of southern Ukraine. At the same time, the efficiency of irrigated agriculture depends not only on providing plants with an adequate amount of water but also on the quality of irrigation water. Elevated mineralization of irrigation water may alter the soil water and salt regime, affect the conditions of plant mineral nutrition, and consequently influence crop yield formation and the quality of plant products.

This issue is of particular importance for forage crops, as, alongside high productivity, the environmental safety of the resulting plant biomass is an essential requirement. The presence of potentially toxic elements in the soil creates conditions for their uptake by plants and incorporation into the “soil–plant–animal” trophic chain. Among the most hazardous contaminants of agricultural land are cadmium (Cd), mercury (Hg), and lead (Pb), the accumulation of which in forage products requires continuous monitoring.

Alfalfa (*Medicago sativa* L.) is one of the major perennial forage crops cultivated under irrigated conditions. Its productivity is determined over several cutting cycles and largely depends on the water regime and soil and climatic conditions. Under such circumstances, assessment based solely on yield does not provide a comprehensive characterization of the efficiency of alfalfa cultivation. It is important to simultaneously determine the effect of irrigation water quality on crop productivity and assess the potential transfer of heavy metals from soil to green biomass, taking into account spatial variations in soil and climatic conditions and the dynamics of individual cut formation.

Therefore, a comprehensive assessment of alfalfa productivity and the environmental safety of its green biomass on irrigated lands of Odesa Region is relevant. Such an assessment should combine the evaluation of the effect of irrigation water mineralization on yield with monitoring of Cd, Hg, and Pb accumulation in forage products. The application of mathematical modelling makes it possible to quantitatively assess these processes under different growing conditions and identify potential risks of obtaining products that do not comply with established safety standards.

Analysis of Recent Research and Publications. Heavy metal contamination of agricultural soils remains an important environmental issue, as their accumulation poses a risk of toxic elements entering plant products and subsequently migrating through trophic chains. Particular attention is given to cadmium (Cd), lead (Pb), and mercury (Hg), which are characterized by persistence in the environment and the ability to accumulate in soils and plants. The intensity of their transfer within the “soil–plant” system is determined not only by the total metal content but also by its bioavail-

ability, which depends on pH, organic matter content, particle-size distribution, and other soil properties [1].

Alfalfa (*Medicago sativa* L.), a valuable forage crop characterized by high productivity and an extensive root system, is of particular interest in studies of heavy metal migration. Chen et al. [2] reported that alfalfa is capable of absorbing potentially toxic elements and activating a range of physiological and biochemical mechanisms of tolerance to metal stress. A substantial proportion of the absorbed elements may accumulate in the root system, whereas their translocation to aboveground biomass depends on the specific properties of the element and growing conditions. Jócsák et al. [3] demonstrated that excessive concentrations of heavy metals may adversely affect alfalfa growth and development, photosynthetic processes, and water and mineral metabolism, while plants are also capable of activating a range of protective mechanisms.

Experimental studies confirm the element-specific response of *M. sativa* to individual heavy metals. For Cd, the bioavailability and accumulation in aboveground biomass have been shown to depend on the properties of the soil environment [4]. Studies of Pb have revealed differences in plant tolerance and the involvement of mechanisms associated with metal transport, root system development, and protective responses [5]. For Hg, its accumulation has been shown to depend on the mobility of its compounds in soil and to be associated with a corresponding response of the alfalfa antioxidant system [6]. Thus, the concentration of heavy metals in aboveground biomass is determined by the interaction of the level of soil contamination, element availability, and the biological characteristics of the crop.

Under irrigated agricultural conditions, the quality of irrigation water represents an additional factor. García-Carrillo et al. [7] identified differences in Pb accumulation in the roots and aboveground parts of alfalfa when different sources of irrigation water were used. Hamoud et al. [8] likewise confirmed the potential accumulation of Cd and Pb in soil and agricultural crops under wastewater irrigation, indicating the need to monitor heavy metal concentrations not only in soil and irrigation water but also directly in forage products.

Thus, recent studies have characterized the patterns of heavy metal uptake and accumulation by alfalfa, as well as the effects of soil conditions and irrigation water quality on these processes. However, quantitative assessment of heavy metal concentration in alfalfa forage biomass, taking into account soil and climatic conditions, water availability, and the productivity of individual cuts, remains insufficiently studied. The application of mathematical modelling provides an opportunity to comprehensively account for these factors and assess heavy metal accumulation in green biomass under different growing conditions.

Aim of the Study. The aim of the study was to assess the effect of irrigation water mineralization on the formation of green biomass yield of second-year alfalfa and to determine the patterns of cadmium (Cd), mercury (Hg), and lead (Pb) accumulation in forage products depending on the level of soil contamination, water availability, natural and climatic and soil conditions of the Odesa Region, and cutting cycle.

Materials and Methods. The methodological basis of the study was a dynamic approach to modelling the processes of crop productivity formation and heavy metal contamination [9], implemented using [name of the dynamic model]. Its application involves comprehensive simulation of the interactions among the main components of the agroecosystem within the “soil–plant–atmosphere” system and makes it possible to simultaneously assess yield formation and the uptake and accumulation of contaminants in plant products.

The modelling approach was based on the assumption that plant growth, development, and productivity formation are determined by the interaction between the biological characteristics of the crop and a set of environmental factors. Biomass formation was simulated by taking into account the synthesis of organic matter through photosynthesis, its distribution between the aboveground and belowground plant organs, and the utilization of assimilates for growth processes. The uptake of mineral nutrients by the root system and their subsequent utilization by plants were also taken into account.

The numerical modelling reproduced the main components of agroecosystem functioning, including the radiation, thermal, and water regimes of the crop, mineral nutrition conditions, as well as soil salinization and sodification processes. A separate model module described heavy metal migration within the “soil–plant” system, including the supply of available forms of contaminants to the root system, their uptake by plants, and their subsequent translocation and accumulation in plant organs.

The modelled object was second-year alfalfa (*Medicago sativa* L.) grown for green biomass production. Yield formation and its environmental characteristics were considered as the result of interconnected physiological and biochemical processes involving the formation, transformation, and accumulation of plant biomass, as well as the uptake and accumulation of contaminants in plants. Alfalfa green biomass yield was used as the productivity indicator, while cadmium (Cd), mercury (Hg), and lead (Pb) concentrations were used as indicators of the environmental safety of the forage product.

For the numerical experiments, agroclimatic, soil, and agroecological characteristics of the Odesa Region were used. The calculations were performed for the natural and climatic zones and subzones and agro-soil provinces represented within the region, taking into account the corresponding soil types. Modelling was conducted for second-year alfalfa separately for the first, second, and third cuts under both natural and regulated water supply conditions.

To assess the effect of irrigation water quality on alfalfa productivity, a series of numerical experiments was performed by varying the total mineralization of irrigation water from 0.4 to 3.0 g/dm³. The interpretation of the results took into account the regulatory criteria for water suitability for irrigation and the environmentally safe management of irrigated agriculture [10–12].

To assess heavy metal contamination of alfalfa green biomass, data on Cd, Hg, and Pb concentrations in the soils of the Odesa Region obtained from agro-

chemical surveys and the certification of agricultural lands were used as initial parameters [13]. Based on these data, model calculations were performed to estimate the uptake and accumulation of the studied metals in alfalfa green biomass under different soil and climatic conditions, water availability, and cutting cycles.

The model-calculated concentrations of Cd, Hg, and Pb in plant biomass, expressed on a dry matter basis, were converted to a standard forage moisture content of 12% to assess the safety of the forage product. The resulting values were compared with the applicable maximum permissible levels of heavy metal concentrations in feed established by the regulatory documents of Ukraine [14, 15].

Results. The modelling results (Fig. 1) demonstrate a consistent decline in alfalfa green biomass yield with increasing irrigation water mineralization from 0.4 to 3.0 g/dm³. At the same time, the magnitude of the crop response was determined by both the cutting cycle and the natural, climatic, and soil characteristics of the study area.

The most pronounced effect of irrigation water quality was observed for the first cut. In the Northern Steppe of the Right-Bank Province, an increase in water mineralization from 0.4 to 3.0 g/dm³ resulted in a decrease in green biomass yield from 26.9 to 23.6 t/ha, i.e., by 3.3 t/ha (12.3%). In the Southwestern Province, the yield decreased from 25.4 to 23.2 t/ha, corresponding to a reduction of 2.2 t/ha (8.7%). In the Southern Steppe of the Right-Bank Province, the decrease was from 29.8 to 27.3 t/ha, or by 2.5 t/ha (8.4%), whereas in the Southern Dry Steppe of the Danube Province, the yield declined from 25.5 to 23.3 t/ha, corresponding to a reduction of 2.2 t/ha (8.6%). Thus, the highest relative sensitivity of first-cut productivity to increasing irrigation water mineralization was observed in the Northern Steppe of the Right-Bank Province.

The high sensitivity of first-cut alfalfa to irrigation water mineralization can be explained by the fact that the most intensive growth and vegetative biomass formation occur in spring. The application of mineralized water during this period increases the concentration of salts in the soil solution, which reduces water uptake by the roots, causes loss of turgor, and inhibits the growth of young stems. During the formation of the second and third cuts, plants adapt to the prevailing growing conditions, activate their endogenous protective mechanisms, and accumulate stress-related compounds, enabling them to tolerate salt stress considerably more effectively.

For the second cut, the negative effect of increased irrigation water mineralization persisted but was less pronounced. Depending on the agro-soil province, at a mineralization level of 0.4 g/dm³, green biomass yield ranged from 20.3 to 28.2 t/ha, whereas at 3.0 g/dm³ it ranged from 19.2 to 26.2 t/ha. The highest productivity level across the entire range of mineralization studied was maintained in the Southern Steppe of the Right-Bank Province, indicating the substantial role of territorial soil and climatic conditions in yield formation alongside irrigation water quality.

In the third cut, the response of yield to changes in water mineralization was even less pronounced, whereas spatial differentiation in productivity became more evident. In the Southern Steppe of the Right-Bank Province, yield decreased from 20.3 to 19.8 t/ha, while in the Northern Steppe of the Right-Bank Province it declined from 19.3 to 18.6 t/ha. Considerably lower productivity was obtained in the Northern Steppe of the Southwestern Province, where yields ranged from 12.4 to 11.9 t/ha, and in the Southern Dry Steppe of the Danube Province, where they ranged from 10.8 to 9.6 t/ha.

Thus, the results of the first series of modelling experiments demonstrated that an increase in irrigation

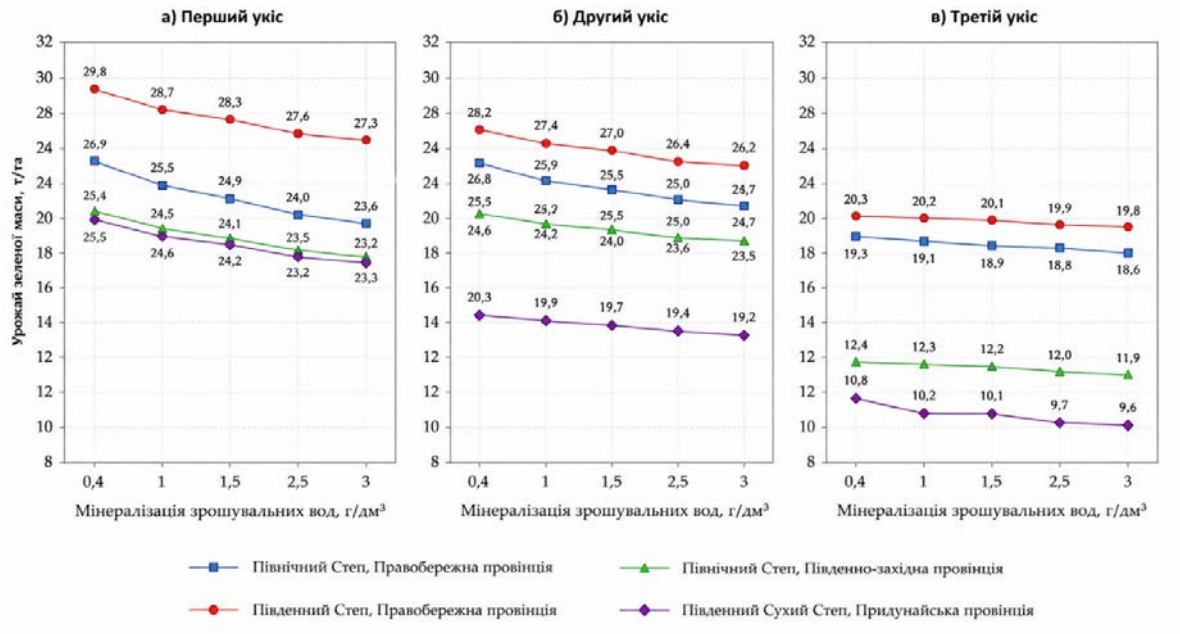


Fig. 1. Relationship between second-year alfalfa green biomass yield and irrigation water quality, Odesa Region

water mineralization was accompanied by a decrease in alfalfa green biomass yield under all the natural and climatic conditions considered. The crop response to deteriorating irrigation water quality was most pronounced in the first cut. In subsequent cuts, the effect of mineralization became weaker, whereas the role of natural, climatic, and soil differences in determining productivity became more pronounced.

The next stage of the study involved assessing heavy metal accumulation in alfalfa green biomass. In this series of modelling experiments, calculations for irrigated conditions were performed at an irrigation water mineralization level of 0.4 g/dm³. The results presented in Table 1 characterize the spatial and within-season variability of Cd, Hg, and Pb concentrations depending on the content of the respective metal in the soil, water availability, and cutting cycle.

For all three metals studied, a general trend toward decreasing concentrations in green biomass from the first to the third cut was observed, although the magnitude of these changes varied among agro-soil provinces. Under rainfed conditions, Cd concen-

Table 1 – Assessment of heavy metal contamination of alfalfa green biomass yield in Odesa Region

Growing conditions	Cutting cycle	Natural and climatic zone (subzone)				
		Forest-Steppe	Northern Steppe		Southern Steppe	Southern Dry Steppe
		Agro-soil province				
		Right-Bank	Right-Bank	Southwestern	Right-Bank	Danube
		Soil				
		Typical chernozem, light clayey	Ordinary chernozem, light clayey	Ordinary chernozem, heavy loamy	Southern chernozem, medium loamy	Dark chestnut, medium-textured loam soil
		Variant 1				
		Cadmium concentration (C_{Cd}) in soil, mg/kg:				
		0,16	0,21	0,17	0,21	0,17
		Cadmium concentration (C_{Cd}) in green biomass, mg/kg:				
Rainfed	1-st	0,0123	0,0158	0,0114	0,0150	0,0114
	2-d	0,0070	0,0088	0,0097	0,0097	0,0097
	3-rd	0,0070	0,0088	0,0053	0,0097	0,0026
Irrigated	1-st	-	0,0114	0,0097	0,0132	0,0097
	2-d	-	0,0079	0,0079	0,0079	0,0088
	3-rd	-	0,0079	0,0044	0,0079	0,0026
		Variant 2				
		Mercury concentration (C_{Hg}) in soil, mg/kg:				
		0,0098	0,0122	0,0108	0,0122	0,0108
		Mercury concentration (C_{Hg}) in green biomass, mg/kg:				
Rainfed	1-st	0,0255	0,0308	0,0255	0,0290	0,0246
	2-d	0,0176	0,0176	0,0211	0,0185	0,0211
	3-rd	0,0141	0,0176	0,0123	0,0185	0,0062
Irrigated	1-st	-	0,0229	0,0202	0,0255	0,0211
	2-d	-	0,0141	0,0176	0,0176	0,0194
	3-rd	-	0,0141	0,0106	0,0106	0,0053
		Variant 3				
		Lead concentration (C_{Pb}) in soil, mg/kg:				
		11,1	15,6	10,8	15,6	10,8
		Lead concentration (C_{Pb}) in green biomass, mg/kg:				
Rainfed	1-st	1,311	1,742	1,135	1,628	1,100
	2-d	0,704	1,144	0,915	1,056	0,942
	3-rd	0,704	1,144	0,537	1,056	0,273
Irrigated	1-st	-	1,294	0,906	1,487	0,915
	2-d	-	0,810	0,774	0,845	0,836
	3-rd	-	0,810	0,458	0,836	0,229

tration in the green biomass of the first cut ranged from 0.0114 to 0.0158 mg/kg, Hg from 0.0246 to 0.0308 mg/kg, and Pb from 1.100 to 1.742 mg/kg. In the third cut, the corresponding ranges decreased to 0.0026–0.0097 mg/kg for Cd, 0.0062–0.0185 mg/kg for Hg, and 0.273–1.144 mg/kg for Pb. Thus, the highest accumulation of the heavy metals studied in aboveground biomass generally occurred during the initial cycle of forage stand utilization.

Under irrigated conditions, Cd, Hg, and Pb concentrations in green biomass were lower in most of the cases considered than under rainfed conditions. Specifically, in the first cut, Cd concentration under irrigation ranged from 0.0097 to 0.0132 mg/kg compared with 0.0114–0.0158 mg/kg under rainfed conditions; Hg concentration ranged from 0.0202 to 0.0255 mg/kg compared with 0.0246–0.0308 mg/kg, while Pb concentration ranged from 0.906 to 1.487 mg/kg compared with 1.100–1.742 mg/kg. A similar trend was generally maintained in the second and third cuts. These results indicate that water availability is one of the factors determining heavy metal concentration in the resulting plant biomass.

The decrease in Cd, Hg, and Pb concentrations in alfalfa green biomass under irrigation can be attributed to the classical physiological dilution effect. Under increased water availability, the rate of organic matter synthesis and biomass accumulation substantially exceeds the rate of heavy metal ion uptake and translocation to aboveground plant organs. In addition, optimal soil moisture promotes the binding of a proportion of metals by the soil adsorption complex, whereas under rainfed conditions during drought, evaporation of the soil solution causes a rapid increase in the concentration of Cd, Hg, and Pb ions in the remaining soil water, thereby enhancing their uptake by plant roots.

To assess the environmental safety of the forage product, the model-calculated heavy metal concentrations, converted to a standard forage moisture content of 12%, were compared with the applicable maximum permissible levels for their concentrations in feed [14, 15]. Under all natural and climatic conditions studied, across different cuts and water availability regimes, the concentrations of Cd, Hg, and Pb in alfalfa green biomass did not exceed the established regulatory limits. The maximum calculated concentrations were 0.0158 mg/kg for Cd, 0.0308 mg/kg for Hg, and 1.742 mg/kg for Pb, whereas the corresponding maximum permissible concentrations were 1.0, 0.1, and 30 mg/kg, respectively.

Thus, the modelling results indicate that, at the studied levels of soil contamination in the Odesa Region, the green biomass of second-year alfalfa meets the established feed safety requirements with respect to Cd, Hg, and Pb concentrations. At the same time, the observed spatial and within-season variability in heavy metal accumulation supports the need for monitoring their concentrations within the “soil–plant” system, particularly during the first cut, for which the highest calculated concentrations of the elements studied were obtained.

CONCLUSIONS:

1. An increase in irrigation water mineralization from 0.4 to 3.0 g/dm³ results in a consistent decrease in the green biomass yield of second-year alfalfa. The greatest biomass losses were observed in the first cut (8.4–12.3%), which can be attributed to osmotic stress during the period of intensive spring vegetative growth.

2. Cd, Hg, and Pb concentrations in alfalfa green biomass exhibit pronounced within-season dynamics, with maximum values observed in the first cut and minimum values in the third cut, corresponding to the intensity of spring uptake of these elements from the soil.

3. Irrigation was found to be a factor contributing to the environmental optimization of forage quality: due to the physiological biomass dilution effect (dilution effect), heavy metal concentrations in irrigated green biomass were 15–25% lower than those in corresponding rainfed biomass.

4. All calculated concentrations at a forage moisture content of 12% – 0.0158 mg/kg for Cd, 0.0308 mg/kg for Hg, and 1.742 mg/kg for Pb – were below the applicable maximum permissible levels for forage products, namely 1.0, 0.1, and 30 mg/kg, respectively, confirming the high agroecological quality of the product.

5. A methodological approach to environmental monitoring has been substantiated, according to which analytical monitoring of alfalfa forage quality and heavy metal concentrations (Cd, Hg, and Pb) should primarily focus on first-cut samples, as they are the most representative of the potential maximum accumulation of toxicants.

6. The feasibility of differentiated irrigation regimes has been established. When using a water source with a high salt concentration (>1.5 g/dm³) during the formation of the first cut, the application of a water-saving irrigation regime is justified, whereas for the second and third cuts, a biologically optimal irrigation regime is appropriate. This differentiation is associated with the increasing physiological tolerance of the forage stand to irrigation water mineralization throughout the growing season.

Конфлікт інтересів: один з авторів є членом редакційної колегії журналу. Для забезпечення незалежності редакційного процесу рукопис розглядався редактором, який не мав конфлікту інтересів з автором. Автор не брав участі у відборі рецензентів, процесі рецензування та прийнятті рішення щодо публікації статті. Рукопис пройшов стандартну процедуру подвійного сліпого рецензування.

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Zhygailo T.S., Zhygailo O.L., Danchuk O.V., Grafov A.V., Kozyrev V.V., Zherebchuk S.V., Piliarska O.O. Assessment and control of heavy metal contamination in alfalfa green mass yield on irrigated lands of Odesa region

Purpose. To assess the effect of irrigation water mineralization on the formation of green mass yield of second-year alfalfa and to determine the patterns of cadmium (Cd), mercury (Hg), and lead (Pb) accumulation in forage depending on the level of soil contamination, water supply conditions, natural-climatic and soil characteristics of Odesa Region, and cutting cycle. **Methods.** The study was conducted using dynamic mathematical modeling of crop productivity formation and heavy metal contamination within the “soil–plant–atmosphere” system. A series of numerical experiments was performed for second-year alfalfa (Medicago sativa L.), taking into account the natural-climatic and agro-soil conditions of Odesa Region. The effect of irrigation water quality on productivity was assessed by varying water mineralization from 0.4 to 3.0 g/dm³. The accumulation of Cd, Hg, and Pb in green mass was modeled for the first, second, and third cuttings under different water supply conditions. The calculated heavy metal concentrations were adjusted to a standard forage moisture content of 12% and compared with the current maximum permissible levels established for feed. **Results.** A consistent decrease in alfalfa green mass yield was observed with increasing irrigation water mineralization. The response was most pronounced in the first cutting, where an increase in mineralization from 0.4 to 3.0 g/dm³ resulted in an 8.4–12.3% decrease in yield, depending on natural-climatic and soil conditions. In the second and third cuttings, the effect of water mineralization became less pronounced, whereas spatial differences in productivity became more evident. Spatial and within-season variability in heavy metal accumulation in the green mass was identified. Under most of the studied conditions, the highest concentrations of Cd, Hg, and Pb occurred in the first cutting and decreased in subsequent cutting cycles. Under irrigation, the concentrations of the studied elements in the green mass were lower in most model variants than under non-irrigated conditions. The maximum calculated concentrations were 0.0158 mg/kg for Cd, 0.0308 mg/kg for Hg, and 1.742 mg/kg for Pb and did not exceed the established maximum permissible levels for forage. **Conclusions.** Irrigation water quality is an important factor affecting alfalfa productivity, with the first cutting showing the greatest sensitivity to increased water mineralization. The accumulation of Cd, Hg, and Pb in green mass is influenced by soil conditions, water supply, and cutting cycle. At the studied levels of soil contamination in Odesa Region, the green mass of second-year alfalfa complied with feed safety requirements for Cd, Hg, and Pb content. The identified patterns can be used for the integrated control of forage productivity and quality on irrigated lands.

Key words: mathematical modeling, forage, water mineralization, agro-soil conditions, water supply, cadmium, mercury, lead.

Жигайло Т.С., Жигайло О.Л., Данчук О.В., Графов А.В., Козирєв В.В., Жеребчук С.В., Пілярська О.О. Оцінка та контроль забруднення урожаю зеленої маси люцерни важкими металами на зрошуваних землях Одещини

Мета. Оцінити вплив мінералізації зрошувальної води на формування врожаю зеленої маси люцерни другого року життя та визначити закономірності накопичення кадмію (Cd), ртуті (Hg) і свинцю (Pb) у кормовій продукції залежно від рівня забруднення ґрунту, умов водозабезпечення, природно-кліматичних і ґрунтових особливостей території Одеської області та укосу. **Методи.** Дослідження проведено із застосуванням динамічного математичного моделювання процесів формування продуктивності сільськогосподарських культур та їх забруднення важкими металами в системі «ґрунт – рослина – атмосфера». Виконано серію чисельних експериментів для люцерни посівної (*Medicago sativa* L.) другого року життя з урахуванням природно-кліматичних та агроґрунтових умов Одеської області. Вплив якості зрошувальної води на продуктивність оцінювали при зміні її мінералізації від 0,4 до 3,0 г/дм³. Накопичення Cd, Hg і Pb у зеленій масі моделювали для першого, другого і третього укосів за різних умов водозабезпечення. Розраховані концентрації важких металів приводили до стандартної вологості корму 12% та зіставляли з чинними нормативами їх максимально допустимого вмісту в кормах. **Результати.** Встановлено закономірне зниження врожаю зеленої маси люцерни зі збільшенням мінералізації зрошувальної води. Найбільш вираженою реакція була у першому укосі, де при підвищенні мінералізації від 0,4 до 3,0 г/дм³ зниження врожаю залежно від природно-кліматичних і ґрунтових умов становило 8,4–12,3%. У другому і третьому укосах вплив мінералізації послаблювався, а територіальні відмінності продуктивності прояв-лялися більш виразно. Виявлено просторову та внутрішньосезонну мінливість накопичення важких металів у зеленій масі. Для більшості досліджуваних умов найбільші концентрації Cd, Hg і Pb формувалися у першому укосі та зменшувалися у наступних циклах скошування. За зрошення вміст досліджуваних елементів у зеленій масі в більшості модельних варіантів був нижчим порівняно з незрошуваними умовами. Максимальні розрахункові концентрації становили 0,0158 мг/кг для Cd, 0,0308 мг/кг для Hg та 1,742 мг/кг для Pb і не перевищували встановлених максимально допустимих рівнів у кормовій продукції. **Висновки.** Якість зрошувальної води є істотним чинником формування продуктивності люцерни, причому найбільша чутливість до підвищення мінералізації характерна для першого укосу. Накопичення Cd, Hg і Pb у зеленій масі визначається ґрунтовими умовами, водозабезпеченням та циклом скошування. За досліджуваних рівнів забруднення ґрунтів Одеської області зелена маса люцерни другого року життя за вмістом Cd, Hg і Pb відповідала нормативним вимогам щодо безпечності кормів. Отримані закономірності можуть бути використані для комплексного контролю продуктивності та якості кормової продукції на зрошуваних землях.

Ключові слова: математичне моделювання, кормова продукція, мінералізація води, агроґрунтові умови, водозабезпечення, кадмій, ртуть, свинець.

Дата першого надходження статті до видання: 23.09.2026
Дата прийняття статті до друку після рецензування: 26.10.2026
Дата публікації (оприлюднення) статті: 13.11.2026

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