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THE EFFECT OF DIFFERENT DOSES OF MIXED LIGAND COMPLEXES OF ZINC, MANGANESE, AND COBALT ON THE MILK PRODUCTIVITY OF DAIRY COWS DURING LACTATION PERIODS

Abstract
Using trace element salts in animal feed can lead to the rapid contamination of the environment with these metals due to their low biological availability to animals. Organic compounds of trace elements are much better absorbed by animals, who perform better at reduced levels of these feed additives. This article presents comprehensive study results on the effect of mixed-ligand complexes

of trace elements (Zn, Mn, and Co) combined with organic selenium (Suplex Se) on the milk productivity of high-yielding cows of various breeds during different lactation periods. The work is relevant due to the increasing deficiency of trace elements in the soil–feed–ration system in intensive dairy farming conditions, and the low bioavailability of traditional inorganic trace element salts. This study aimed to demonstrate the feasibility of replacing sulfate forms of zinc, manganese, and cobalt with mixed ligand complexes and to establish the optimal concentrations of these complexes in cow diets during the lactation period. The experiment was conducted on 50 cows from three breeds (German Holstein, Ukrainian Black-and-White Dairy, and Ukrainian Red-and-White Dairy) using the analogue group method, forming one control group and four experimental groups. Productivity, milk quality, and feed consumption were studied over the first, second, and third 100-day periods of lactation. We have established that using organic forms of micronutrients reliably increases the average daily milk yield ($P < 0.001$), enhances gross milk production with a 4 % fat content, and reduces metabolic energy expenditure per unit of production. The highest milk productivity rates during the first 100 days were achieved with a diet containing 60.8 mg of zinc (Zn), 60.8 mg of manganese (Mn), and 0.78 mg of cobalt (Co) per kg of dry matter (DM) in the form of mixed ligand complexes. During the second 100 days, an optimal effect was achieved with lower concentrations of trace elements (35 mg Zn and Mn, and 0.4 mg Co per kg of DM). Using chelated forms of trace elements also led to a moderate increase in milk's fat and protein content, as well as a 4–6 % reduction in feed consumption. The results confirmed that the source of these trace elements in the diet is their mixed-ligand complexes. Dairy cows require less than the recommended amount of zinc, cobalt, and manganese.

Key words: *high-yield cows, milk productivity, mixed-ligand complexes, organic trace elements, milk quality, milk fat and protein.*

Introduction. Feed and feed additives provide high-yielding cows with essential nutrients, such as proteins, fats, carbohydrates, and minerals, as well as biologically active substances, including trace elements and vitamins. Theoretical and practical data from studies of animal metabolism and energy exchange confirm this. These studies are based on advances in biochemistry, physiology, microbiology, and the chemical composition and properties of feed. They also consider the effects of various nutrients and biologically active substances on feed efficiency, product synthesis, reproductive function, and animal health [9].

High-yielding cows have an intense exchange of energy and nutrients within their bodies. Therefore, their vital functions, metabolic processes, resistance, productivity, and reproductive capacity depend not only on the necessary intake of proteins, fats, and carbohydrates from feed but also on biologically active substances [11].

According to recommendations by a group of scientists led by G.O. Bogdanov [35], the concentrations of zinc and manganese should be 70 mg/kg of dry matter (DM), cobalt should be 0.9 mg/kg DM, copper should be 11 mg/kg DM, iodine should be 1 mg/kg DM, and selenium should be 0.3 mg/kg DM for high-yielding cows with an average daily milk yield of 35 kg or more.

In recent years, industrial dairy farming in Ukraine has increasingly revealed a lack of micronutrients in the soil-feed-ration chain, as well as a higher demand for these nutrients due to increased milk yields from high-producing cows. Under these conditions, the issue of micronutrient nutrition for high-yielding cows arises, as their bodies require specific amounts and ratios of essential micronutrients [15].

Trace elements have been established as biologically active substances that affect the metabolism of proteins, fats, and carbohydrates in animals because they are essential components or activators of many enzymes and hormones. Additionally, trace elements strengthen the immune system and influence reproductive functions and animal productivity [4]. A lack of zinc primarily reduces protein synthesis in animals, leading to stunted growth and reduced fertility in both females and males [14; 27]. A lack of manganese in the diets of dairy cows leads to impaired fatty acid synthesis, paralysis, sterility, abortions, and skeletal deformities in both cows and their newborn calves [29]. Cobalt deficiency, like vitamin B_{12} deficiency, leads to anemia, sexual dysfunction, and reduced resistance to infections in animals [26]. Combining selenium with vitamin E in the diets of lactating and dry cows optimizes rumen fermentation, increases feed nutrient digestibility, improves blood redox reactions and reproductive function, and enhances the viability and growth of young stock [13; 21]. Copper deficiency leads to decreased cellulase activity, impaired function of hematopoietic organs and endocrine glands, and hindered oxidative-reductive processes and protective reactions in the body. It also impairs the growth and reproduction of animals [14]. Iodine deficiency causes growth and developmental delays in young animals, decreases protein, carbohydrate, and fat metabolism, and reduces oxygen absorption by tissues, as well as the oxygen utilization coefficient. It also decreases the activity of many enzymes and the vital activity of microorganisms in the forestomachs of ruminants, as well as the animal's resistance [8]. In dairy cows, a deficiency of copper, zinc, manganese, cobalt, iodine, and selenium in their diet reduces the digestibility of nutrients, particularly roughage and succulent feed. Due to decreased enzymatic activity in the forestomach, the availability of feed energy and its efficiency for livestock production and reproductive function decrease [8]. Similar findings have been obtained for poultry [28; 30; 23; 25], pigs [5; 24; 16], bulls [10], and rabbits [2] regarding the increase in milk productivity of cows when fed lower doses of organic compounds of zinc, manganese, and cobalt. Additionally, using their highly bioavailable organic forms to reduce the overall level of micronutrients in diets is of significant environmental importance, as it helps reduce anthropogenic environmental impact [3].

Until recently, sulfate and chloride compounds were the traditional sources of mineral salts in livestock feed. However, these compounds' metals are easily transformed into hydroxide systems with low bioavailability in the gastrointestinal tract. They also exhibit antagonistic effects on each other and generally hurt the animal's body. Therefore, even an adequate amount of inorganic zinc, manganese, cobalt, and selenium salts in the diet can lead to deficiencies because the body is adapted to absorbing organic, chelated minerals found in plants. The low digestibility of inorganic minerals increases the risk of environmental pollution because the body does not absorb them but rather excretes them. Additionally, the crystallized water contained in sulfate molecules can destroy metal and vitamins in premixes.

The constant need to replenish trace elements in animals' bodies, which must enter living organisms in biologically active forms, has prompted scientists to seek new sources of these elements. The most promising sources are metal compounds with biologically active substances, such as amino acids, peptides, proteins, nucleic acids, carbohydrates, and carboxylic acids. Trace elements found in organic compounds have a positive effect on the intensity of microflora development, increasing the efficiency of digestion and fermentation of feed in the digestive tract and making feed more accessible to bacteria [7; 18].

Zinc, manganese, and cobalt are essential for the proper functioning of enzymes, structural proteins, and cellular proteins. Compared to their inorganic counterparts, organic complexes of Zn, Mn, and Co exhibit higher bioavailability, which improves the physiological condition and productivity of cows, particularly during the transition period and early lactation [19; 12; 31]. According to Osorio et al. [20], lactation stress due to an insufficient supply of micronutrients can exacerbate metabolic disorders. However, Andrieu [1] found that balancing the diet with organic micronutrients minimizes the effects of metabolic destabilization.

The Research Institute (RI) of Ecology and Biotechnology at Bila Tserkva National Agrarian University (BNAU) produces metal chelate complexes, which are compounds formed by combining metals with amino acids, such as lysine and methionine. Scientists from the Department of Feed Production, Feed Additives, and Animal Feeding developed a method to enrich feed grain with micronutrients. This method transforms inorganic micronutrients into organic compounds known as mixed ligand complexes. However, before using these chelates in combination with Suplex Se to feed high-yielding domestic and foreign cows, it is necessary to thoroughly study their effects on animal metabolism, productivity, and reproductive functions, taking into account the breed and stage of lactation.

The purpose of the work. The research aimed to address the mineral nutrition problem of high-yielding cows by replacing the sulfates of zinc, manganese, and cobalt in the recommended premixes with their organic compounds in protease compositions. These compositions were subsequently named mixed-ligand complexes of zinc, manganese, cobalt, and selenium (Se).

Presentation of the main research material. Experimental studies were conducted at the Terezyne Limited Liability Company's dairy complex in the Bila Tserkva district of the Kyiv region. These studies also took place at the Department of Feed Technology, Feed Additives, and Animal Feeding, as well as in the Feed and Livestock Product Analysis laboratory, the Biochemical and Histochemical Research Methods laboratory, and the Animal Disease Diagnostics laboratory of the Research Institute of Agricultural Animal Nutrition and the Research Institute of Internal Animal Diseases of the BNAU.

Studies of the actual content of trace elements in feed have shown that high-yielding cow diets often lack essential elements such as copper, zinc, manganese, cobalt, iodine, and selenium.

To find the best doses of zinc, manganese, and cobalt mixed ligand complexes during lactation, experiments were conducted using various concentrations of these complexes per kilogram of dry matter (DM) in the feed mixture.

The scientific and economic experiment employed the analog group method, which involved forming experimental groups of highly productive cows based on their physiological and productive characteristics [34; 33]. The 300-day study was divided into two periods: a 20-day preparatory period and an observation period lasting up to 300 days of lactation.

Fifty cows were selected for the scientific and economic experiment, including twenty Holstein cows of German selection, fifteen Ukrainian black-and-white dairy cows, and fifteen Ukrainian red-and-white dairy cows. Five groups of analogous cows were formed from the total livestock population, each comprising 10 animals. One control group and four experimental groups (groups 2, 3, 4, and 5) were selected from these groups (Table 1). However, during the experiment, one cow injured its limb, resulting in the removal of this animal and its analogues from the experiment. Consequently, during the second and third 100-day periods of lactation, there were nine animals in each group.

In experimental studies, the effects of mixed ligand complexes of zinc, manganese, and cobalt, as well as Suplex Se, were examined in relation to copper sulfate and potassium iodide. The study focused on how these factors impact digestion processes, metabolism, milk productivity, milk quality, and feed costs per unit of milk produced.

According to Table 1, the experimental cows were fed the same feed mixtures, which included compound feed concentrates (CFCs) with a premix containing zinc, copper, and cobalt sulfates to supplement their diets, as well as Suplex Se to supplement their selenium intake to 0.3 mg/kg of DM. The cows in the control group did not receive micronutrient supplements containing zinc, manganese, or cobalt in their premix during the first 100 days of lactation. However, sodium selenite, copper sulfate, and potassium iodide were added to the premix of the control group. Therefore, the cows' feed mixture was deficient in zinc, manganese, and cobalt. The feed mixture for the cows in the second experimental group was supplemented with these nutrients using inorganic compounds. All control and experimental groups of subsequent experiments, as well as the other experimental groups of the first scientific and economic experiment, were fed a mixed ligand complex of zinc, manganese, cobalt, and sodium selenite instead of zinc, manganese, cobalt, and selenite sulfates.

In the first scientific and economic experiment, cows in the third experimental group were provided with the recommended amount of zinc, manganese, and cobalt in the form of mixed ligand complexes. Cows in the other experimental groups were given different doses of these nutrients per kilogram of dry matter in their diet. The diets of the

Table 1. Plan of a scientific and economic experiment

Group	Number of heads	The studied factor
The first 100 days of lactation		
Preparatory period of the experiment (20 days)		
1 control	10	Feed mixture (FM) + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 32.4; Manganese – 27.8; Cobalt – 0.27; Selenium – 0.3; Copper – 12; Iodine – 1.1
2 experimental	10	Feed mixture (FM) + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 32.4; Manganese – 27.8; Cobalt – 0.27; Selenium – 0.3; Copper – 12; Iodine – 1.1
3 experimental	10	Feed mixture (FM) + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 32.4; Manganese – 27.8; Cobalt – 0.27; Selenium – 0.3; Copper – 12; Iodine – 1.1
4 experimental	10	Feed mixture (FM) + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 32.4; Manganese – 27.8; Cobalt – 0.27; Selenium – 0.3; Copper – 12; Iodine – 1.1
5 experimental	10	Feed mixture (FM) + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 32.4; Manganese – 27.8; Cobalt – 0.27; Selenium – 0.3; Copper – 12; Iodine – 1.1
Observation period of experiment (80 days)		
1 control	10	Feed mixture (FM) + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 32.4; Manganese – 27.8; Cobalt – 0.27; Selenium – 0.3; Copper – 12; Iodine – 1.1
2 experimental	10	FM + sulfates of Zinc, Manganese, Cobalt and Copper + Suplex Se + Potassium iodide. 1 kg of DM contains, mg: Zinc – 76; Manganese – 76; Cobalt – 0.97; Copper – 12; Selenium – 0.3; Iodine – 1.1
3 experimental	10	FM + mixed ligands complex (MLC) of Zinc, Manganese, Cobalt + Suplex Se + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 76; Manganese – 76; Cobalt – 0.97; Selenium – 0.3; Copper – 12; Iodine – 1.1
4 experimental	10	FM + MLC of Zinc, Manganese, Cobalt + Suplex Se + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 60.8; Manganese – 60.8; Cobalt – 0.78; Selenium – 0.3; Copper – 12; Iodine – 1.1
5 experimental	10	FM + MLC of Zinc, Manganese, Cobalt + Suplex Se + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 49; Manganese – 49; Cobalt – 0.63; Selenium – 0.3; Copper – 12; Iodine – 1.1
The second 100 days of lactation		
1 control	9	FM + MLC of Zinc, Manganese, Cobalt + Suplex Se + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 65; Manganese – 65; Cobalt – 0.8; Selenium – 0.3; Copper – 10; Iodine – 0.9
2 experimental	9	FM + MLC of Zinc, Manganese, Cobalt + Suplex Se + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 50; Manganese – 50; Cobalt – 0.7; Selenium – 0.3; Copper – 10; Iodine – 0.9
3 experimental	9	FM + MLC of Zinc, Manganese, Cobalt + Suplex Se + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 45; Manganese – 45; Cobalt – 0.6; Selenium – 0.3; Copper – 10; Iodine – 0.9
4 experimental	9	FM + MLC of Zinc, Manganese, Cobalt + Suplex Se + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 40; Manganese – 40; Cobalt – 0.5; Selenium – 0.3; Copper – 10; Iodine – 0.9
5 experimental	9	FM + MLC of Zinc, Manganese, Cobalt + Suplex Se + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 35; Manganese – 35; Cobalt – 0.4; Selenium – 0.3; Copper – 10; Iodine – 0.9
The last 100 days of lactation		
1 control	9	FM + MLC of Zinc, Manganese, Cobalt + Suplex Se + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 50; Manganese – 50; Cobalt – 0.7; Selenium – 0.3; Copper – 9; Iodine – 0.8
2 experimental	9	FM + MLC of Zinc, Manganese, Cobalt + Suplex Se + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 45; Manganese – 45; Cobalt – 0.6; Selenium – 0.3; Copper – 9; Iodine – 0.8
3 experimental	9	FM + MLC of Zinc, Manganese, Cobalt + Suplex Se + Copper sulfate + Potassium iodide. 1 kg of DM contains, mg: Zinc – 40; Manganese – 40; Cobalt – 0.5; Selenium – 0.3; Copper – 9; Iodine – 0.8
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cows in all experiments consisted of farm-available feed based on its actual nutritional value. The rations were adjusted several times throughout the experiments to account for the cows' milk productivity. Bulk feed was recorded daily for each group separately, or based on data from decadal control feedings. Concentrated and mineral feeds were also recorded daily.

The experimental studies were conducted in accordance with the General Ethical Principles of Animal Experiments (Ukraine, 2001), which aligns with the law On the Protection of Animals from Brutal Treatment (No. 3447-IV, June 21, 2006, amended July 15, 2021) (https://zakon.rada.gov.ua/laws/show/3447-15#n8) and the European Convention for the Protection of Vertebrate Animals used for Experimental and Other Scientific Purposes (ETS No. 123, Strasbourg, 1986) (https://rm.coe.int/168007a67b).

A statistical analysis of the results was performed using Statistica software to calculate the arithmetic mean (x) and standard deviation (± SD). A one-way ANOVA was used to determine statistically significant differences between the mean values for the respective groups of cows. When comparing the data, we calculated statistically significant differences between the mean values for the respective groups. Results were considered statistically significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$.

Feeding cows diets with different levels of zinc, manganese, and cobalt in mixed ligand complexes resulted in changes in productivity. During the first 80 days of the experimental period and the final 100 days of lactation, animals in the fourth experimental group demonstrated the highest productivity. However, during the second 100 days of lactation, animals in the fifth experimental group achieved the highest productivity (Fig. 1).

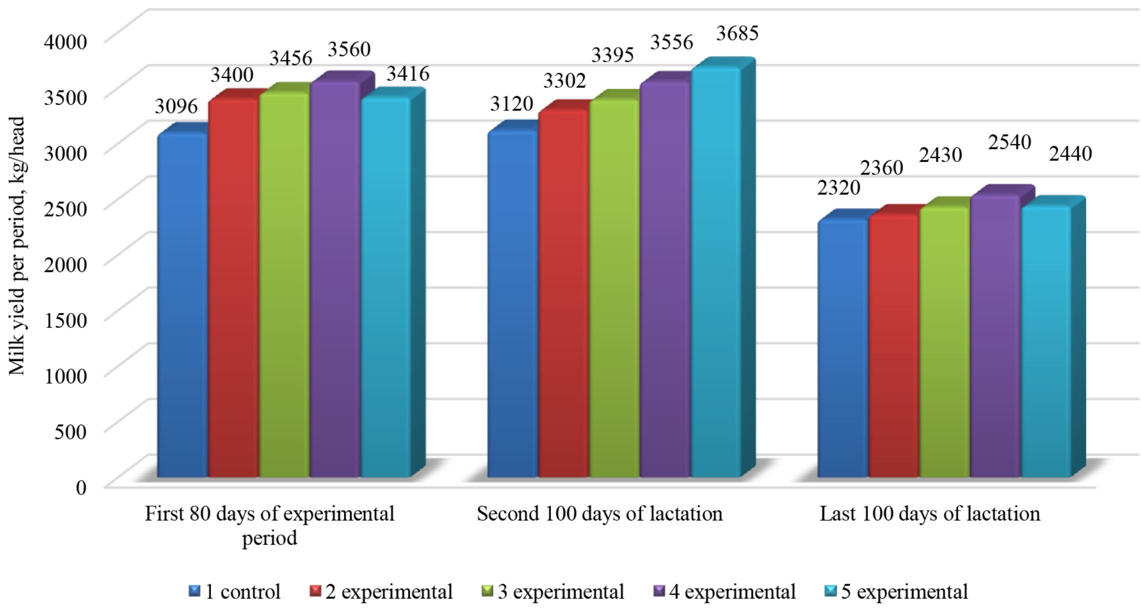

Fig. 1. Productivity of experimental cows fed a diet containing mixed-ligand complexes of zinc, manganese, cobalt, and Suplex Se, kg/head/lactation period

Milk productivity of experimental cows during the first 100 days of lactation. Balancing the feed mixture of high-yielding cows with trace elements (zinc, manganese, and cobalt) in the form of mixed ligand complexes and Suplex Se ensured a direct correlation between milk yield and these indicators (Table 2).

According to Table 2, there was no significant difference in the average daily milk yield or fat content among the experimental cows during the preparatory period of the experiment. However, during the experimental period, a significant difference was observed in the average daily yield of natural and 4 % milk.

The cows in the third, fourth, and fifth experimental groups were most susceptible to lactation during the experimental period. These cows' diets included mixed ligand complexes of zinc, manganese, and cobalt in combination with Suplex Se, copper sulfate, and potassium iodide. Consequently, their average daily milk yield exceeded that of the control group by 3.8, 4.5, 5.8, and 4.0 kg (9.82 %, 11.63 %, 14.99 %, and 10.34 %, respectively). This difference was significant. Meanwhile, the average daily milk yield in the second experimental group, in which micronutrient deficiencies were addressed using zinc, manganese, and cobalt sulfate, was 3.8 kg, or 9.82 %, higher than the average daily milk yield in the first control group. The milk from the experimental cows also had an increased fat content of 0.01–0.09 %.

The current study found that using mixed ligand complexes of trace elements resulted in higher milk yields during the first 100 days and the middle period of lactation. The current study found that using mixed-ligand complexes of trace elements resulted in higher milk yields during the first 100 days and the middle period of lactation. The highest indicators of early lactation were observed in cows whose diets contained organic forms of zinc (Zn), manganese (Mn), and cobalt (Co) in combination with Suplex selenium (Se), copper sulfate, and potassium iodide (KI). Their average daily milk yield was 9.82–14.99 % higher than the control, which aligns with the findings of Nocek et al. [19] and Hackbart et al. [12]. Furthermore, the fat and protein content of the experimental cows' milk increased, indicating the positive effects of organic micronutrients on lipid and protein metabolism.

Table 2. Productivity of experimental cows during the first 100 days of lactation fed a diet containing mixed-ligand complexes of zinc, manganese, cobalt, and Se supplement ($x \pm$ SD, $n = 10$)

Indicator	Animal group				
	experimental				
	1 control	2 experimental	3 experimental	4 experimental	5 experimental
Average daily milk yield during the preparatory period, kg:					
Natural fat content	31.8 ± 0.48	32.0 ± 0.51	31.5 ± 0.52	31.4 ± 0.47	31.6 ± 0.46
Fat content in milk, %	3.68 ± 0.019	3.64 ± 0.014	3.65 ± 0.018	3.64 ± 0.015	3.63 ± 0.014*
Average daily milk yield for 80 days of the observation period of the experiment, kg:					
Natural fat content	38.7 ± 0.48	42.5 ± 0.44***	43.2 ± 0.40***	44.5 ± 0.39***	42.7 ± 0.41***
4 % fat content	35.8 ± 0.31	39.4 ± 0.36 ***	40.3 ± 0.39***	42.2 ± 0.35***	40.0 ± 0.42***
Fat content in milk, %	3.70 ± 0.028	3.71 ± 0.032	3.73 ± 0.026	3.79 ± 0.023*	3.75 ± 0.030
Protein content in milk, %	3.05 ± 0.025	3.06 ± 0.023	3.07 ± 0.028	3.09 ± 0.028	3.06 ± 0.024
Gross milk yield per cow for 80 days of lactation, kg (observation period)					
Natural fat content	3096 ± 14.88	3400 ± 15.62***	3456 ± 14.99***	3560 ± 13.68***	3416 ± 16.63***
4 % fat content	2864 ± 13.88	3152 ± 14.52***	3224 ± 12.99***	3376 ± 18.03***	3200 ± 15.40***

Note: different letters within each row indicate significant differences between groups according to the Tukey's HSD test results

The average daily milk yield advantage was also significant compared to the control group, amounting to 3.6 kg ($P < 0.001$), or 10.06 %, in the second experimental group; 4.5 kg ($P < 0.001$), or 12.56 %, in the third experimental group; 6.4 kg ($P < 0.001$), or 17.88 %, in the fourth experimental group; and 4.2 kg ($P < 0.001$), or 11.73 %, in the fifth experimental group.

The analysis of data obtained during the experiment revealed that the cows in the control group produced 2,864 kg of milk with 4 % fat content over the course of 80 days. Meanwhile, the cows in the second, third, fourth, and fifth experimental groups produced 288 kg, 360 kg, 512 kg, and 336 kg more milk, respectively, which is 10.1 %, 12.5 %, 17.9 %, and 11.7 % more milk.

The milk of cows in the experimental groups showed a slight increase in protein content compared to the control group (3.06–3.09 % versus 3.05 %).

The cows in the fourth experimental group produced the most milk. They received a feed mixture containing mixed ligand complexes of zinc, manganese, cobalt, and Suplex Se, as well as copper sulfate and potassium iodide. One kilogram of this mixture contains 60.8 mg of zinc, 60.8 mg of manganese, 0.78 mg of cobalt, 0.3 mg of selenium, 12 mg of copper, and 1.1 mg of iodine.

The main indicator of milk production efficiency is feed consumption per kilogram of milk produced. Studies show that for cows producing milk with varying levels of zinc, manganese, and cobalt in their diets, feed consumption decreases as milk productivity increases. During the study period, the lowest feed consumption per kilogram of natural fat milk was observed in the fourth experimental group of cows. These cows were fed a diet containing 60.8 mg of zinc, 0.78 mg of manganese, 0.3 mg of selenium, 12 mg of copper, and 1.1 mg of iodine per kilogram of DM.

According to the data in Figure 2, a relationship exists between the energy value of the diet and the level of micronutrient supply in 1 kg of dry feed mixture. Although the control group had the highest metabolic energy (ME) value, its diet contained the lowest levels of zinc, manganese, and cobalt.

Despite the lower energy value of the feed, the concentration of trace elements was significantly higher in the experimental groups, resulting in improved metabolic processes in the cows. The most pronounced positive effect was observed in the fourth experimental group, which received optimal levels of trace elements at the lowest ME value. This group had the highest milk yield during the first 100 days of lactation.

Analysis of the data in Figure 3 shows a correlation between micronutrient levels in the diet and digestible protein utilization efficiency during the first 100 days of lactation. The control group, which had the lowest micronutrient content, had the highest digestible protein consumption per 1 kg of milk.

In experimental groups where zinc, manganese, and cobalt were supplied as mixed ligand complexes, protein consumption decreased consistently. The fourth experimental group had the lowest consumption, which is the best indicator among all options. This group had optimal levels of trace elements (60.8 mg Zn and Mn; 0.78 mg Co per kg of DM), ensuring the most efficient protein utilization during peak lactation.

In the second and third experimental groups, where zinc (Zn) and manganese (Mn) levels were higher, protein consumption increased. In the fifth group, where the micronutrient supply was lower, protein consumption increased to 95.9 g, which was higher than in the other groups but lower than the control values.

Milk yield of experimental cows during the second 100 days of lactation. Despite the diets in the given feed mixture having the same energy, protein, carbohydrate, and fat content, the milk productivity of cows in the experimental and control groups differed due to their different consumption of the feed (Table 3).

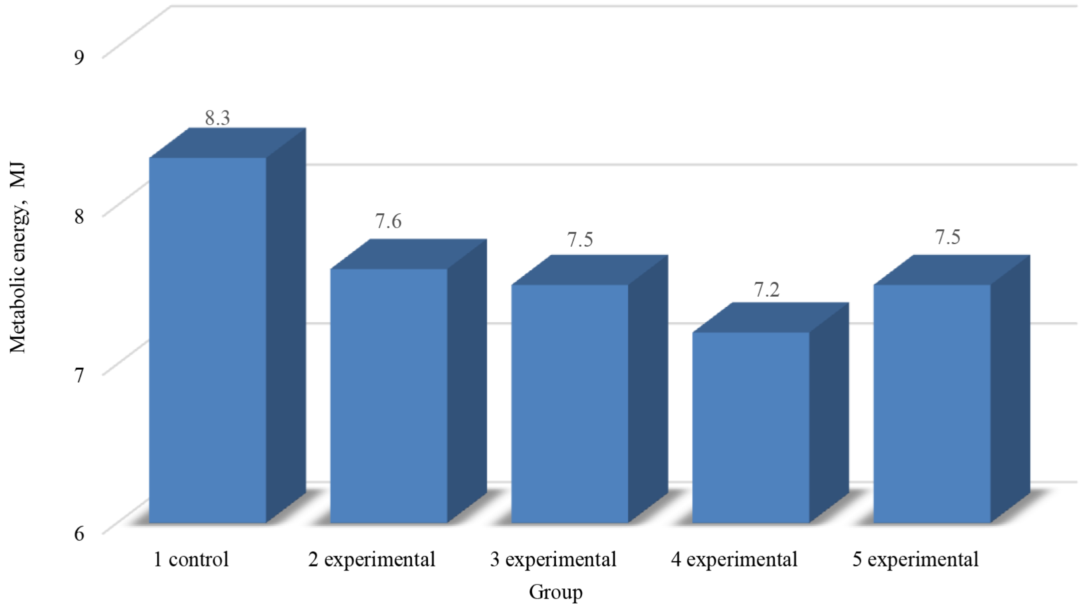

Fig. 2. Metabolic energy consumption per 1 kg of milk of natural fat content during the first 100 days of lactation when feeding cows mixed ligand complexes of zinc, manganese, and cobalt with Suplex Se, MJ

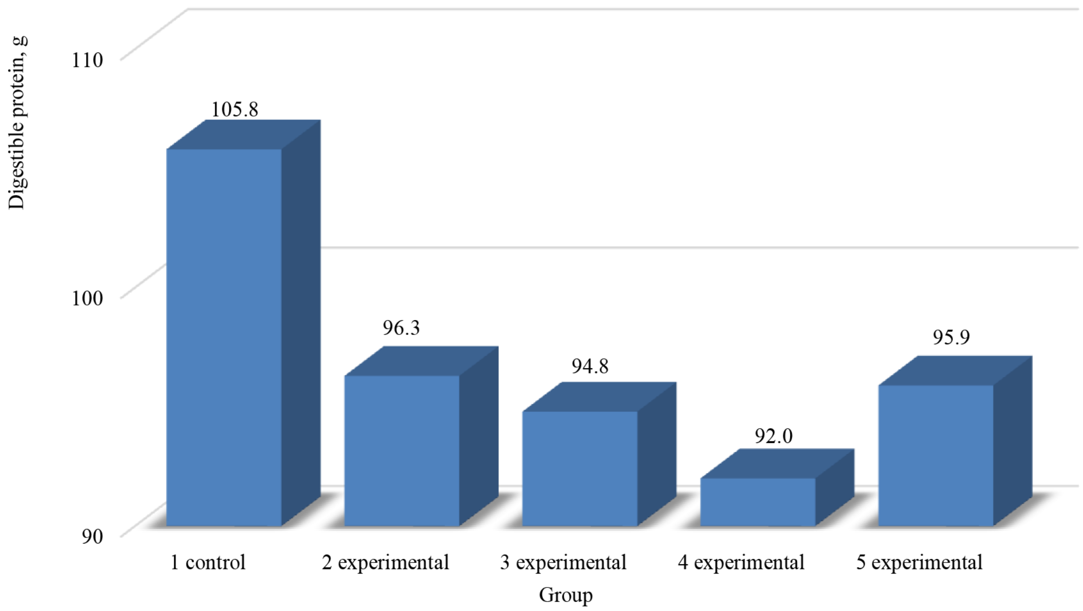

Fig. 3. Digestible protein consumption per 1 kg of natural fat milk during the first 100 days of lactation when feeding cows a diet containing mixed ligand complexes of zinc, manganese, cobalt, and Suplex Se, g

During the second 100 days of lactation, if each cow in the control group produced 3.120 kg of raw milk, then the cows in the second and fourth experimental groups produced 182–565 kg more. The average daily milk yield difference ranged from 1.82 to 5.65 kg. The milk of the experimental cows also showed an increase in fat content of 0.01 % to 0.02 %. Converting the average daily yield of natural milk to milk with 4 % fat content reveals the following differences between the control and experimental groups: 2nd group, 1.85 kg (6.38 %, $P < 0.01$); 3rd group, 2.72 kg (9.37 %, $P < 0.001$); 4th group, 4.32 kg (14.89 %, $P < 0.001$); and 5th group, 5.53 kg (19.06 %, $P < 0.001$).

Compared to the control group, the milk from the experimental groups had a slightly higher protein content (3.32 %–3.34 % versus 3.31 % in the control group).

Since the nutritional value of the cows' diets in all experimental groups was nearly identical, but milk yields varied, differences in feed consumption per kilogram of milk also occurred. Meanwhile, cows in the experimental groups consumed 0.13 % to 4.26 % less metabolic energy for milk production than the control group.

A significant reduction in feed costs per kilogram of milk, particularly for cows in the fourth group, indicates greater nutrient conversion when organic forms of zinc (Zn), manganese (Mn), and cobalt (Co) are used. Similar results were reported by Yamamoto et al. [31], March et al. [17], and Rabiee et al. [22], who observed increased feed consumption and milk yield with organic micronutrient supplementation.

Table 3. Cow productivity during the second 100 days of lactation when fed a diet containing mixed ligand complexes of zinc, manganese, cobalt, and Suplex Se ($x \pm SD$, $n = 9$)

Indicator	Animal group				
	1 control	2 experimental	3 experimental	4 experimental	5 experimental
Milk yield per cow, kg	3120	3302	3395	3556	3685
% to control	100	105.83	108.81	113.97	118.11
Average daily yield of natural milk, kg	31.20	33.02	33.95	35.56	36.85
Fat content in milk, %	3.72 ± 0.029	3.74 ± 0.038	3.74 ± 0.031	3.75 ± 0.025	3.75 ± 0.037
Average daily milk yield 4 % fat, kg	29.02 ± 0.348	30.87 ± 0.487	31.74 ± 0.301**	33.34 ± 0.359***	34.55 ± 0.358
% to control	100.00	106.38	109.37	114.89	119.06
Protein content in milk, %	3.31 ± 0.028	3.32 ± 0.049	3.33 ± 0.026	3.33 ± 0.047	3.34 ± 0.039
Feed consumption per cow, MJ ME	24,200	25,560	26,240	26,920	27,340
Feed consumption per 1 kg of milk with 4 % fat content, MJ OE	7.75	7.74	7.73	7.57	7.42

Note: see Table 1

Cows in the fifth experimental group produced the most milk. Their feed mixture contained 35 mg of zinc, 35 mg of manganese, 0.4 mg of cobalt, 0.3 mg of selenium, and 0.9 mg of iodine per 1 kg of DM.

Milk yield of experimental cows during the last 100 days of lactation. The consumed feed provided average daily milk yields of 24–26 kg/day in terms of metabolic energy, 25–27 kg/day in terms of dry matter, 27–28 kg/day in terms of crude protein, 28–30 kg/day in terms of digestible protein, and sugar – 22–23 kg/day.

Table 4 shows the average milk yield of the cows under study over the last 100 days of lactation. According to Table 4, during the initial period of incorporating different levels of zinc, manganese, and cobalt into the experimental cows' diets, milk productivity was not significantly affected. While the control group produced an average of 2.320 kg of raw milk during the third 100 days of lactation, the experimental groups produced between 40 and 220 kg more.

Table 4. Cow productivity during the last 100 days of lactation when fed a diet containing mixed ligand complexes of zinc, manganese, cobalt, and Suplex Se ($M \pm m$, $n = 9$)

Indicator	Animal group				
	1 control	2 experimental	3 experimental	4 experimental	5 experimental
Milk yield per cow, kg	2320	2360	2430	2540	2440
Average daily yield of natural milk, kg	23.2	23.6	24.3	25.4	24.4
Fat content in milk, %	3.82 ± 0.029	3.84 ± 0.038	3.89 ± 0.031	3.91 ± 0.025*	3.95 ± 0.037**
Gross milk yield of 4 % fat per cow, kg	2216.0	2266.0	2363.0	2483.0	2409.0
Average daily milk yield of 4 % fat content, kg	22.16 ± 0.132	22.66 ± 0.157*	23.63 ± 0.122**	24.83 ± 0.138***	24.09 ± 0.129***
% to control	100	102.26	106.63	112.05	108.71
Protein content in milk, %	3.33 ± 0.042	3.33 ± 0.051	3.35 ± 0.036	3.34 ± 0.043	3.34 ± 0.059
Feed consumption per 1 cow, MJ OE	19870	20260	20560	20950	20260
Feed consumption per 1 kg of 4 % fat milk, MJ OE	8.97	8.94	8.70	8.44	8.41
% to control	100	99.7	97.0	94.1	93.7

Note: see Table 1

The difference in average daily milk yield between the control and experimental groups was only 0.4–2.2 kg of milk. It should be noted that the less mixed ligand complexes of zinc, manganese, and cobalt were added to the feed mixture, the higher the milk yield obtained from the experimental cows. An increase in fat content was observed in the milk of the experimental cows at the end of lactation. However, this increase, ranging from 0.02 % to 0.13 %, was greater in the experimental groups. The increase in milk fat and higher milk yields with natural fat content significantly increased the difference in gross yields of milk with 4 % fat content. The difference in this indicator between the second experimental group and the control group was 50.0 kg (2.26 %). In the third experimental group, the weight was 147.0 kg (6.63 %) ($P < 0.01$). In the fourth experimental group, the weight was 267.0 kg (12.04 %) ($P < 0.001$). In the fifth experimental group and the control group, the weight was 193.0 kg (8.71 %) ($P < 0.001$). The protein content in the milk of the test cows increased at the end of lactation, averaging 3.33 % to 3.34 %.

Since the cows in the experimental groups consumed slightly more feed, their bodies received more metabolic energy, which was offset by increased milk yield. Therefore, the difference in feed consumption per kilogram of milk was lower for the cows in the experimental groups. Cows in the experimental groups consumed 0.3–6.3 % less metabolic energy to produce milk than cows in the control group.

Conclusions. According to a comprehensive assessment, the optimal doses of zinc, manganese, and cobalt for highly productive cows during the first 100 days of lactation are 60.8 mg, 60.8 mg, and 0.78 mg per 1 kg of DM feed mixture, respectively. Mixed ligand complexes provided these doses and were 20 % lower than the recommended levels. Consuming complete feed mixtures with specified concentrations of trace elements in mixed-ligand complexes increases milk yield by 15 % and increases the proportion of fat and protein in milk.

During the second 100 days of lactation, cows that consumed a feed mixture containing 35 mg of zinc, 35 mg of manganese, and 0.4 mg of cobalt per 1 kg of DM showed higher productivity indicators, with milk productivity increasing by 19 % compared to the control group.

During the final 100 days of lactation, cows that consumed a feed mixture containing 1 kg of zinc (35 mg), manganese (35 mg), and cobalt (0.4 mg) produced the best results. These cows outperformed the control group by 2.2 kg in terms of milk yield.

The best productivity results during the last 100 days of lactation were achieved by cows whose feed mixture contained 35 mg of zinc, 35 mg of manganese, and 0.4 mg of cobalt per 1 kg of DM. These cows outperformed the control group by 2.2 kg in terms of milk yield.

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ВПЛИВ РІЗНИХ ДОЗ ЗМІШАНОЛІГАНДНИХ КОМПЛЕКСІВ ЦИНКУ, МАНГАНУ І КОБАЛЬТУ НА МОЛОЧНУ ПРОДУКТИВНІСТЬ ДІЙНИХ КОРІВ ЗА ПЕРІОДАМИ ЛАКТАЦІЇ

Анотація

Використання солей мікроелементів у годівлі тварин призводить до стрімкого забруднення навколишнього середовища цими металами через їхню низьку біологічну доступність для тваринного організму. Органічні сполуки мікроелементів значно краще засвоюються в організмі тварин, які проявляють кращу продуктивність за зменшених рівнів цих кормових добавок. У статті представлено результати комплексних досліджень впливу змішанолігандних комплексів мікроелементів (Zn, Mn, Co) у поєднанні з органічною формою селену (Суплекс Se) на молочну продуктивність високопродуктивних корів різних порід за різних періодів лактації. Актуальність роботи зумовлена зростанням дефіциту мікроелементів у системі ґрунт–корм–раціон в умовах інтенсивного молочного скотарства, а також низькою біодоступністю традиційних неорганічних солей мікроелементів. Мета дослідження – обґрунтувати доцільність заміни сульфатних форм цинку, мангану й кобальту на змішанолігандні комплекси та визначити їх оптимальні концентрації у раціонах корів упродовж лактаційного періоду. Експеримент проведено на 50 коровах трьох порід (голштинської породи німецької селекції, української чорно-рябої молочної породи та української червоно-рябої молочної породи) методом груп-аналогів із формуванням однієї контрольної та чотирьох дослідних груп. Вивчали продуктивність, якість молока та витрати кормів у перші, другі та треті 100 днів лактації. Встановлено, що використання органічних форм мікроелементів забезпечує достовірне підвищення середньодобових надоїв, збільшення валового виробництва молока 4 % жирності та зниження витрат обмінної енергії на одиницю продукції. Найвищі показники молочної продуктивності у перші 100 днів отримано у корів, раціони яких містили 60,8 мг Zn, 60,8 мг Mn та 0,78 мг Co/кг СР у вигляді змішанолігандних комплексів. Упродовж других 100 днів оптимальний ефект забезпечували нижчі концентрації мікроелементів (35 мг Zn і Mn та 0,4 мг Co/кг СР). Застосування хелатних форм мікроелементів сприяло також помірному зростанню вмісту жиру й білка в молоці та зниженню витрат кормів на 4–6 %. Отримані результати підтвердили, що дійні корови потребують меншу від рекомендованої кількість цинку, кобальту та мангану за умови, що джерелом цих мікроелементів у раціоні є змішанолігандні їх комплекси.

***Ключові слова:** високопродуктивні корови, молочна продуктивність, змішанолігандні комплекси, органічні мікроелементи, якість молока, жир і білок молока.*

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